

CHAPTER 3

Diverse Challenges Explored with Unified Spirit:

Ames in the 1970s and 1980s

Two events make 1969 the year to mark the next era in Ames history. First, Apollo 11 returned safely from its landing on the Moon, signalling the beginning of the end of the lunar landing mission that drove NASA almost from its start. NASA had yet to decide what to do for its second act, and a flurry of strategic planning took place against an uncertain political backdrop. Much of the American public--including both political conservatives concerned with rampant inflation and political liberals concerned with technocratic government--began to doubt the value of NASA's big plans. NASA had downplayed the excitement of interplanetary exploration as it focused on the Moon. Congress and the American aerospace industry, under pressure from a resurgent European aerospace industry, began to doubt if NASA really wanted the aeronautics part of its name. NASA had to justify its budget with quicker results, better science, and relevance to earthly problems.

The second major event of 1969 was the arrival of Hans Mark as Ames director. Mark, himself, displayed a force of personality, a breadth of intellect, and an aggressive management style. More significantly, Mark arrived as rumors circulated that Ames would be shut down. Thus, Ames people gave him a good amount of room to reshape their institution. An outsider to both Ames and NASA, Mark forged a vision for Ames that nicely translated the expertise and ambitions of Ames people with the emerging shape of the post-Apollo NASA. Mark fashioned Ames to epitomize the best of what NASA called its OAST Centers--those reporting to the Office of Aerospace Science

and Technology. Mark left Ames in 1977, but became in effect an ambassador for the Ames approach to research management during his posts at the Defense Department and at NASA headquarters.

Into the 1970s, NASA increasingly focused its work on the Space Shuttle, taking the posture that access to space would soon be routine. Ames responded to this mission, first, by creating technologies that would make the Shuttle as routine as other aircraft and second, by showing that there was still room within NASA for the extraordinary. This was a period at Ames when what mattered most was entrepreneurship, reinvention, and alliance-building. Ames reshaped itself, so that the institutional structures that mattered most included the Ames Basic Research Council, the Ames strategy and tactics committee, quality circles, and Ames-university consortia agreements. Ames more consciously developed its people, so that Ames people played ever larger roles in NASA administration.

]Redefining the Directors' Role: Hans Mark[

Like Ames directors tend to be, Hans Mark was a practicing researcher. But he was the first senior executive at Ames who did not come up through its ranks. Mark was born 17 June 1929 in Mannheim, Germany, and emigrated to America while still a boy. He got an A.B. in 1951 in physics from the University of California and a Ph.D. in 1954 in physics from the Massachusetts Institute of Technology. He then returned to Berkeley and, save for a brief visit to MIT, stayed within the University of California system until 1969. He started as a research physicist at the Lawrence Radiation Laboratory in Livermore and rose to lead its experimental physics division. He also rose through the faculty ranks to become professor of nuclear engineering at the Berkeley campus. In 1964 he left his administrative duties at Lawrence Livermore National Laboratory to become chair of Berkeley's nuclear engineering department as it shifted its emphasis from weapons to civil reactors.

When he arrived at Ames, Mark applied many of the management techniques he had witnessed at work in the nuclear field. He created a strategy and tactics committee that allowed for regular discussions among a much broader group than just upper management, about where Ames was going and what would help it get there. As a result, Ames people became very good at selecting areas in which to work. Tilt rotors, for example, brought together a wide array of research at Ames to tackle the problem of air traffic congestion. Ames deliberately pioneered the new discipline of computational fluid dynamics by acquiring massively parallel supercomputers and merging scattered code-writing efforts into a coherent discipline that benefitted every area at Ames.

Similarly, Mark created the Ames "murder" board. This board was a sitting group of critics that questioned anyone proposing a new project or research area, to toughen them up for the presentations they would make at headquarters. His style was argumentative, which he thought Ames needed in its cultural mix. In a period of downsizing, Mark wanted Ames people to stake out "unassailable positions"--program areas that were not just technically valuable but that they could defend from any attack.

From his experience at Livermore, Mark also understood the power of matrix organization, the idea then underlying the restructuring of all research and development in the military and high-technology industry. Though formal matrix organization fitted Ames badly--because of the traditional structure around disciplinary branches and functional divisions--Mark used the murder board to get people thinking about the on-going relationship between functional expertise and time-limited projects. Ames took project management more seriously, using the latest network scheduling techniques to complement its tradition of foreman-like engineers. And Ames bolstered the functional side of its matrix, by getting its scientific and facilities staffs to more consciously express their areas of expertise.

Ames people insisted that Mark understand that they were each unique--willing to be herded but never managed. Mark compromised by mentally grouping them as two types. Some wanted to become as narrow as possible in a crucial specialty that only NASA would support, because academia or industry would not. Mark admired these specialists, but took the paternal attitude that they were incapable of protecting themselves. Others warmed to the constant and unpredictable challenges of aerospace exploration, and constantly reinvented themselves. So Mark created an environment of opportunities, perhaps unique in NASA, where both types of researchers flourished. And Mark adopted the Ames custom of motivation and management by meandering. Like Harvey Allen before him, Mark poked his head randomly into offices to ask people what they were up to, and took it as his responsibility to understand what they were talking about. When he did not have time to stride rapidly across the Center, he would dash off a hand-written memo (that people called Hans-o-grams) that concisely presented his point of view. When scientists like R.T. Jones and Dean Chapman suggested Mark could know a bit more about the work done at the Center, they convened a literature review group that met every Saturday morning after the bustle of the week. While at Ames Mark learned to fly just so he could argue with aerodynamicists and flight mechanics.

Mark treated NASA headquarters in the same informal way. He encouraged Ames people to see headquarters as more than an anonymous source of funds and headaches. Mark showed up every morning at six o'clock so his workday was synchronized with eastern time. He travelled constantly to Washington D.C., taking a red eye flight there and an evening flight back. He attended every meeting he thought important and told anyone who would listen how Ames was shaping its future. There, too, he would poke his head randomly into offices to chat with the occupants about how to shape NASA strategy. To head the Ames directorates of aeronautics, astronautics, and life sciences, Mark picked entrepreneurs who were likewise willing to

travel and sell. Their deputies would stay home and manage daily operations. From Mark, headquarters got the impression that Ames would be more involved in deciding how its expertise would be used. They also got the impression that Mark had a "stop me if you can" attitude toward headquarters and shared little respect for chains of command.

Mark also made Ames collaborate with broader communities. NASA headquarters was often too rule-bound or unimaginative to fund every program Ames wanted to accomplish. Collaboration increased the opportunities for direct funding. Collaboration also made Ames people think about the larger scientific and educational constituencies it served, and increased the chances that all the best people would contribute to Ames' efforts. Mark broke open the fortress mentality that DeFrance had inculcated, and encouraged everyone to put out tentacles in whatever way they thought appropriate.

During Mark's tenure Ames forged on-going ties with universities. While Ames had long used individual contracts with area universities for specific types of help, in 1969 Ames signed a cooperative agreement with Santa Clara University that was open-ended. Negotiated by Ames chief counsel Jack Glazer, it further pushed the limits of the Space Act of 1958. The agreement defined an on-going infrastructure of collaboration so that Ames and university scientists only needed to address the technical aspects of their work together. Furthermore, students could come to Ames to write their dissertations, and many did in the fields of lunar sample analysis and computational fluid dynamics. Some students came to write papers on the law of space, research, or intellectual property, since Glazer had made his office the only legal counsel office in NASA with a research budget. Rather than being a contract with research bought solely for NASA's benefit, the collaborating universities shared substantially in the cost of research. Ames signed collaborative agreements with universities around America so that in June 1970, when President Nixon tried to appoint a government czar of

science to keep university faculty out of the the pockets of mission-oriented agencies like NASA, Ames stood out as exemplary on the value of collaboration at the local level. In 1971 headquarters let Ames award grants as well as administer them; by 1976 Ames' university affairs office could administer the grants independent of the procurement office. By 1978, Ames administered 260 grants to 110 universities with annual obligations of more than \$11 million.

Mark also encouraged Ames researchers to interact more freely with engineers in industry, and allowed them more freedom to contract with firms most willing to help build products for Ames' needs. Mark encouraged the Army to augment its rotorcraft research office at Moffett Field, and opened dialogue with the Federal Aviation Administration (FAA) about joint programs. Mark put the Illiac IV supercomputer on the Arpanet to encourage a much wider community to write its code. And he encouraged Ames senior staff to seek advancement throughout the Administration. He was especially proud that people nurtured in Ames' atmosphere were named director at Lewis and Goddard (John M. Klineberg), director at Langley (Richard Peterson), associate administrator for management at headquarters and deputy director at Dryden (John Boyd).

Mark left Ames in August 1977, having guided Ames people to shape a long-term vision of where they wanted to go. He helped match their creative energy with NASA's larger and ever-shifting ambitions. The next three directors of Ames shaped the Center in the same way, but with an ever evolving palette of personnel against a changing canvas of scientific progress and international politics. Although none hit Ames with the same amount of youthful energy and cultural dissonance, each of these directors learned his approach by watching Mark at close range. In fact, Mark's very first decision as director was to confirm the decision by NASA headquarters that his deputy would be Clarence Syvertson.

Clarence A. Syvertson:

Clarence "Sy" Syvertson understood the NACA culture that had made Ames so great. He arrived at Ames in 1948, after taking degrees at the University of Minnesota and after a stint in the Army Air Forces, to work with Harvey Allen solving the problems of hypersonic flight. Syvertson then worked with Al Eggers in the 10 by 14 inch wind tunnel until 1959, when he was named chief of the 3.5 foot hypersonic tunnel that he designed. By pioneering theories that could be tested in Ames' complex of wind tunnels, Syvertson outlined the aerodynamic limits for some aircraft that NASA still hopes to build--a hypersonic skip glider, direct flight-to-orbit aircraft, and hypersonic transports. For the North American B-70 bomber, he defined the high-lift configuration later incorporated in other supersonic transport designs. Syvertson also managed the design and construction of the first lifting body, the M2-F2, a prototype wingless aircraft that could fly back from orbit and land at airfields on Earth. A successful series of flight tests in 1964 with the M2-F2 guided the configuration of the Space Shuttle orbiter.

In 1964 Syvertson created and led the NASA mission analysis division, based at Ames but staffed from all NASA Centers, which charted dramatic ways to explore the outer planets. In 1966 Syvertson became director of astronautics, then in 1969 became deputy director of Ames. Syvertson was awarded NASA's Exceptional Service Medal in 1971 for serving as executive director of the joint DOT-NASA Civil Aviation Research and Development policy study that made key recommendations on civil aviation and helped move Ames into air traffic issues.

As Mark's deputy, Syvertson was the inside man. He managed the internal reconfiguration of Ames so that Mark could focus on its future and on its relations with Washington. He managed renovation of the main auditorium so that Ames people could present lectures, award ceremonies and media events in a better setting. Syvertson was known as a consensus-builder--able to step in, forge compromise, and resolve the conflict that Mark

had encouraged, be it policy warfare with headquarters or argumentation internally. When Mark left Ames in 1976, NASA headquarters actually advertised the job of Ames director. After a year, the "acting" was removed from Syverston's position and he was made permanent director because, many people noted, Ames could not survive another Mark.

Ames grew more slowly during Syvertson's tenure, and the pace of contracting in support services accelerated. But Syvertson broke ground for some important new facilities at Ames--like the crew-vehicle systems research facility and the numerical aerospace simulation facility--and extended its collaboration in new areas. Syvertson accelerated Ames' outreach efforts, especially to pre-college students. The teacher resource center, for example, archived slides, videos and other media that science educators could borrow to improve their classes. Class tours grew more frequent, so Syvertson helped form a hands-on teaching museum, which ultimately opened in October 1991 as the Ames Aerospace Encounter built in the old 6 by 6 foot wind tunnel.

Perhaps the biggest challenge to Syvertson and Ames management came in 1981 with Ames' consolidation of the Dryden Flight Research Center. Soon after headquarters had sent Ames' aircraft to Rogers Dry Lake in 1959, Ames started adding aircraft back to its fleet at Moffett Field--first helicopters and VTOL aircraft, then airborne science platforms. When the Reagan administration demanded that NASA cut its staff by 850, acting administrator A. M. Lovelace responded by implementing a plan to make Wallops Flight Center an administrative unit of Goddard and Dryden an "operational element and component installation" of Ames.¹ The merger, effective 1 October 1981, formalized a strong relationship. Ames researchers already performed most of their test flights at Dryden; and most of Dryden flight projects originated at Ames. Both of the Ames-based tilt-rotor aircraft had been flying at Dryden, and Ames willingly transferred more research aircraft there now that its staff was ultimately in charge.

The consolidation was implemented by Louis Brennwald, as Ames director of administration, with consolidation planning led by John W. Boyd, then Ames' associate director and a deputy director at Dryden from 1979 to 1980. Both aeronautics and flight systems directorates were completely reorganized, without requiring reductions in force or involuntary transfers. Consolidation meant that Dryden administered flight operations there, where it was cheaper and safer, and Ames provided technical leadership and policy guidance.

The Ames-Dryden Flight Research Facility sat on the edge of Rogers Dry Lake, a vast, hard-packed lake bed near the town of Muroc in the Mojave desert of southern California. Its remote location, extraordinarily good flying weather, exceptional visibility, and 65 square mile landing area all made it a superb test site. Edwards AFB managed the site, and NASA's Western Aeronautical Test Range provided the tracking and telemetry systems to support the research. Ames-Dryden also ran the world's best facility for remotely piloted flight, and its flight loads research facility allowed ground-based structural and thermal test of aircraft, as well as calibration of test equipment. With better access to Dryden facilities, Ames researchers more efficiently moved innovative designs from concept to flight. To move from concept to flight, Ames had computational power for aerodynamic design and optimization, wind tunnels for measuring loads and fine-tuning configurations, simulators to study handling qualities, and shops to build the proof-of-concept vehicles. The best examples of Ames' abilities to move ideas in to flight quickly and cheaply are the AD-1 oblique wing aircraft, the HiMAT remotely piloted high-g research vehicle, and the F-8 digital fly-by-wire program.

Eventually, Ames had to address the Reagan administration's demand for staff cuts. In 1983 a program review committee led by deputy director Gus Guasterro decided to cut back on new space projects to support existing ones, and to mothball several research facilities--the 14 foot tunnel, the 3.5 foot

hypersonic tunnel, the transportation cab simulator, and the vertical acceleration and roll device. Yet Ames continued to pursue the same broad areas it had staked out as unassailable in the early 1970s. Aeronautical research focused on testing methodologies, safety studies, and slow-speed technologies and vertical takeoff aircraft. Space research focused on thermal protection and spacecraft configurations, adding infrared astronomy and airborne sciences, as well as extending the Pioneer efforts into probes of planetary environments. All Ames research efforts were infused with its ability to build outstanding laboratory tools--wind tunnels, test models, and motion and work simulators. Most notably, supercomputing permeated everything so that written computer code seemed to replace the scientific theory that had earlier guided so much of what Ames did. By Syvertson's retirement in January 1984, Ames had bolstered its prominence within NASA and among wider communities.

]Flight Research[

Leonard Roberts served as Ames director of aeronautics and flight systems from 1972 through 1984, when integrative projects dominated. He helped match all Ames facilities--the tunnels, computers, simulators, and the test grounds at Dryden--with important new flight research programs in maneuverability, short takeoff and landing aircraft, and aircraft safety. Ames grew especially adept at building light, inexpensive, and well-focused flying laboratories to verify component technology, to test seemingly bizarre new configurations, or to gather data that could not be gathered otherwise.

Another airborne research platform arrived at Ames in April 1977. Lockheed originally built the YO-3A as an ultra-quiet spy plane. The sailplane wings, muffled engine, and slow-turning, belt-driven propeller kept the YO-3A quiet enough that Ames and Army researchers could add microphones to the wing-tips and tail-fin to accurately measure noise from nearby aircraft. Ames and Army researcher used the converted YO-3A primarily for studying

helicopter noise. The test aircraft flew behind the Y0-3A, while on-board aero-acoustic measurements were synchronized with data on flight and engine performance telemetered from the test aircraft. Again, based on this research, the FAA asked Ames to play a larger role in research in flight noise mitigation.

Digital Flight Controls:

Exemplifying this integrative urge--especially between researchers at Ames and Dryden--was digital fly-by-wire technology (DFBW). Engineers at Ames had pioneered the concept of digital fly-by-wire in the 1960s, expecting it to replace the heavy and vulnerable hydraulic actuators still used in high-performance aircraft. Ames had already designed many of the electronic controls for its ground-based flight simulators, which were made digital in order to run programs stored on their computers. Making these codes and controls reliable enough for a flying aircraft, however, required a magnitude greater of integration and testing. So they acquired an F-8 Crusader fighter aircraft, removed all the mechanical controls, and installed their best DFBW technology. In 1972 in the air above Ames-Dryden, they first demonstrated the system.

Once Ames had demonstrated the feasibility of DFBW, they worked to provide hardware and programming code that the aerospace industry could use in any new aircraft. Any bug in a multiple channel digital system, like DFBW, could crash all redundant channels and all redundant hardware. To avoid the cost, complexity and weight of a backup system, Ames designed software that could survive any problem in the main program. They further designed this fault-tolerant software to check itself automatically during flight. Other Ames scientists working in computational fluid dynamics applied algorithms that incorporated nonlinear functions into the software, and thus allowed DFBW to expand the flight envelope to the extremes of turbulence and boundary layer separation. The success of fly-by-wire in the

Ames-Dryden tests convinced NASA to use it as the Space Shuttle flight control system.

Ames next applied its skills to the equally complex, multichannel task of controlling jet engines. Ames designed a digital electronic engine control (DEEC) that could optimize the ten variables on the F100 engine that powers the F-15 and F-16 fighter aircraft. Electronic control greatly improved engine performance, with higher thrust, faster throttle response, improved afterburner response, stall-free operation, and eight times better reliability and maintainability than the mechanical controls it replaced. The Ames DEEC first flew on a NASA F-15 in 1982 and, suitably revised by McDonnell Douglas to military specifications, entered production on U.S. Air Force models in 1985.

Ames continued integrating the components of its digital control technology. In the skies over Ames-Dryden, on 25 June 1985, a group of engineers led by program manager Gary Trippensee witnessed the first flight of the NASA F-15 which had been modified as the HIDEDEC aircraft (for highly integrated digital electronics control). By integrating data on altitude, Mach number, angle of attack, and sideslip, HIDEDEC let the aircraft and engine operate very close to the stall boundary. Simply by improving these controls, and reducing the stall margin, thrust improved two to ten percent. The next phase of the Ames-Dryden HIDEDEC program included flight path management, by adding a digital flight controller built by Lear Siegler Corp. for the Air Force. This technology optimized trajectories to minimize fuel consumption, suggest faster intercepts, and allow navigation in four dimensions. The FAA asked Ames to expand upon this flight path controller in order to help improve capacity in the commercial airspace system. So Ames developed a set of algorithms to process data from aircraft sensors into cockpit instructions on how a pilot could fly more efficiently. The Ames algorithm found its way onto new Boeing 757 and 767 and Airbus A310

aircraft, and the airlines estimated Ames' work saved them four percent on fuel costs.

Ames-Dryden staff then used the F-15 flight research aircraft to develop self-repairing flight controls. In flight tests during May 1989, sensors and computers aboard the F-15 correctly identified a simulated failure in the flight controls. Diagnosing failures on the ground is always time consuming, and often fruitless since the failures can only be identified during specific flight conditions. Once the system identified the failure, it could reconfigure other parts of the aircraft to compensate.

Ames powerful triad of facilities--tunnels, computers, and simulators--allowed it to create and prove the fundamental hardware and software that controls all recent aircraft. It also created protocols useful in the increasing integration of electronics and software in flight systems. And it validated the use of airborne laboratories---like the F-8 and the F-15--to quickly and cheaply validate the importance of component technologies.

Research Aircraft:

Ames also drove development of new experimental aircraft. In the early 1960s, for example, Ames aerodynamicist R.T. Jones worked out the theory behind the oblique wing. The wing was perpendicular to the fuselage at take-off to provide maximum lift, then swiveled in flight so that one half-span angled forward and the other angled backward to decrease drag. This shape could solve the transonic problems of all naval aircraft, which needed high lift to get off a carrier and a sleek profile to go supersonic. Swept wings, like those on the F-111, solved this problem by using a joint that was heavier and weaker than the swivel joint needed to support an oblique wing.

Aerodynamically, however, the oblique wing was very complex. First, the airfoil had to provide lift with air moving over it at a variety of angles. Second, flight controls had to be sophisticated enough to compensate for the asymmetry of the control surfaces. Ames' ongoing work in digital fly-by-wire

made it easier to design the oblique wing, by enabling programmers to write code to control an inherently unstable aircraft.

Jones had already established his reputation in theoretical aerodynamics. He saw in the oblique wing not only a promising concept and an intellectual challenge, but also a program to validate Ames' integrative approach to flight research. Jones marshalled the full scientific resources of Ames--especially its wind tunnels and computer modeling--to design the experimental aircraft called the AD-1 (for Ames-Dryden). Then, the AD-1 was fabricated quickly and cheaply, using sailplane technology and a low-speed jet engine. By taking this low cost approach, Jones quickly validated the concept and assessed flying qualities without the bureaucratic squabbles that usually accompany X-series aircraft.

Soon after the AD-1's first flight, in 1987, the U.S. Navy joined Ames to sponsor the Grumman X-29A. The X-29's bizarre aerodynamics had both wings swept forward and a canard for lateral axis control. Because it was inherently unstable, the X-29 took full advantage of the flight control software and digital fly-by-wire technologies developed at Ames-Dryden. One other research aircraft developed at Ames validated the concepts and technology behind the X-29A.

The HiMAT, which first flew in July 1979, was specifically designed for flights tests of high-maneuverability concepts. HiMAT (for highly maneuverable aircraft technology test bed) was a Dryden project until Ames was called in to help solve some aerodynamic problems. William Ballhaus wrote the codes to solve three-dimensional, transonic, small-perturbation equations that marked the first time that computational fluid dynamics had been used to design a wing. (Later this code was used to design the wing for the Sabreliner and for the B-2 stealth bomber, establishing Ballhaus' reputation in applied CFD.) Dryden and Ames staff built the HiMAT as a small-scale, remotely-piloted, and heavily-instrumented aircraft to test out risky technology. At a fraction of the time and cost of a human-carrying

vehicle, Ames tested the interactions between many new high-maneuverability devices on an aircraft in flight. HiMAT included digital fly-by-wire, relaxed static stability, close-coupled canards, and aeroelastic tailoring. Aeroelastic tailoring of composite materials allowed Ames to construct wings so that airflows twisted them to the optimum camber and angle, whether at cruise speeds or undergoing heavy g-loading during maneuvers. Tests of aeroelastic tailoring on the HiMAT provided valuable data on the use of composite materials in all modern aircraft.

Flight Test Technologies:

Perhaps because Ames people directed work at Dryden, there was a flourish of research into ways of improving the correspondence between tunnel tests and flight tests. For example, Ames designed a remotely augmented vehicle to expand its skills in flight test instrumentation. This vehicle collected data using the same sensors that collected data during flight tests, telemetered it to a computer on the ground, which transmitted back commands to the flight controls to augment the aircraft's performance. This ground-based computer was easy to maintain and upgrade, flexible enough to control several test aircraft, and powerful enough to run more sophisticated software than was possible on flight-approved computers. Ames used this technology to test new artificial intelligence algorithms before preparing them for inclusion in flight controllers. And it proved a far more efficient way in which to take the next step forward in variable-stability flight-test aircraft.

Similarly, Ames' flight-test autopilot was a digital computer into which engineers programmed an exact flight-test maneuver. Since this test autopilot was patched directly into the on-board flight controls, there was no need for additional actuators. The pilot could, of course, override it at any time, but it proved especially valuable when a pilot had to simultaneously perform many maneuvers and control many flight variables, or when repeatability of a maneuver was important.

Ames-Dryden pilots also developed the technology of the transition cone. To scale results from wind tunnel models up to full-scale aircraft, aerodynamicists needed to understand where boundary layers made the transition from laminar to turbulent flow. Researchers at the Arnold Engineering Development Center originated the transition cone concept, which pilots and flight test engineers at Ames-Dryden then tested at a variety of Mach numbers in wind tunnels and mounted to the nose cone of NASA's F-15. They obtained data that set standards, used worldwide, on the quality of airflows in wind tunnels.

NASA's high-alpha technology program was an effort to calibrate its many research tools while exploring an intriguing regime of aerodynamics. For twelve weeks beginning in June 1991, an Ames team led by Lewis Schiff tested a Navy F/A-18 in the 80 by 120 foot section of the NFAC, making it the first full-scale aircraft tested in the world's largest wind tunnel. The goal was to understand how a modern fighter aircraft performed at very high angles of attack (called high alpha) like those encountered in aerial combat. Wind tunnel data were matched against the data predicted by computational fluid dynamics, and both were compared with flight-test data collected on a highly instrumented F/A-18.

FAA/DOT/NASA Safety, Workload, and Training Studies:

Beginning with its first research effort, in aircraft de-icing, Ames had pursued specific projects to make aircraft safer and more efficient. Into the 1970s, Ames attacked the problems of aircraft safety with a comprehensive agenda of research projects.

Ames opened its flight simulator for advanced aircraft (FSAA), in June 1969, initially to analyze concepts for the cockpits of the Space Shuttle and fighter aircraft. It soon became the key part of an increasingly comprehensive collection of facilities dedicated to flight simulation and was used to conduct experiments on how to improve pilot workloads, aircraft automation, flight

safety, airline efficiency and, later, air traffic control. Ames researchers then broadened its use to encompass the entirety of the national airspace system. Ames built an alliance with the FAA, which had a research laboratory for its applied research but did little basic science, and the newly created Department of Transportation which had not yet developed its research capability. Ames brought into this flight safety partnership the full range of its capabilities--in communications, simulation, materials science, and computing.

The FAA asked Ames, for example, to devise an aviation safety reporting system (ASRS) to collect data--supplied voluntarily by flight and ground personnel--on aircraft accidents or incidents in U.S. aviation. The Ames human factors group, led by Charles Billings, brought every involved group into the planning, and ASRS director William Reynard implemented it expertly and fairly. The ASRS won the trust of pilots and air traffic controllers, who initially balked at reporting incidents because these incidents almost always arose from simple human error. Ames did not collect the data anonymously, since they had to verify them, but removed identification before compiling data for the FAA. In its first fifteen years, ASRS received 180,000 safety reports, at a rate of 36,000 a year by 1991. From this massive database on human performance in aviation, Ames staff generated hundreds of research papers that led to improvements in aviation safety. The ASRS also put out periodic alert messages about matters that required immediate attention, and a monthly safety report. "There's nothing worse than sending information to a government agency," said Reynard, "and seeing nothing happen."²

Using these data to locate weak spots in the system, Ames used its simulators to minimize human errors. One protocol tested on the simulators became known as line-oriented flight training (LOFT) a method devised at Ames for training crews in all facets of a flight. Previous methods of training and crew testing focused on their response to emergency situations. Because they were maneuver-oriented, these methods tended to generate

programmed responses. Line-oriented training used a large-scale simulator which recreated an entire flight from point to point, interjecting complex problems along the way to test the coordination of decision-making. Airlines adopted a version of it, as did the U.S. Air Force and the FAA.

In the late 1970s, during the full-flight simulations underlying line-oriented training, Ames discovered that most accidents occurred not because pilots lacked technical skill, but because they failed to coordinate all the resources available in the cockpit. Paradoxically, most training focused on technical proficiency with individual parts of the cockpit. So the Ames aeronautical human factors branch developed methods for use in training pilots to manage all cockpit resources. Ames and the U.S. Air Force Military Airlift Command organized a conference, attended by more than 200 aircraft safety experts from 14 countries, that established the importance of training pilots in cockpit resource management.

This work then led to better workload prediction models, which Ames used to devise simulation scenarios subjecting pilots to standardized workloads. From this the U.S. Air Force adopted a single code (to simulate supervisory control) to promote its pilots, and NASA adopted a target-selection code to evaluate control devices for the Space Shuttle. Ames continued to study theories of cockpit automation to reduce pilot error, and then built these into the crew-vehicle systems research facility (CVSRF). Opened in 1984, the facility encompassed all facets of air traffic control--air-to-ground communications, navigation, as well as a computer-generated view out of the simulated cockpit. Ames used this facility to test, cheaply and quickly, all types of proposed improvements to cockpits and air traffic control systems.

Material scientists at Ames focused on aircraft fire safety. Data showed that the number of passengers who survived an aircraft fire was largely determined by their egress time and by the flammability of the aircraft seats. As a result, John Parker, an expert on foam-making, designed a seat of

conventional urethane foam and covered it with a fire-blocking felt that is both fire resistant and thermally stable. In addition, the new seats were easy to manufacture and maintain, durable, comfortable, and lightweight. In controlled fire tests done by the FAA on a C-133 and a B-720, passengers escaped the post-crash fires one minute faster than with earlier seats. Based on these tests, in October 1984 the FAA issued a new regulation on the flammability of aircraft seats. By October 1987, more than 600,000 seats were retrofitted, at a cost estimated at \$22 million. Twenty-five lives each year that might be lost in fires are spared, it is estimated, because of these seats. John Parker and Demetrius Kourtides of Ames' chemical research project branch continued to work on fire-resistant materials, especially lightweight composite panels. Though an interesting and useful application of materials science to flight safety, into the 1990s Ames' expertise in writing complex software fueled the expansion of its work for the FAA in flight safety.

Upgrading the Wind Tunnels:

Ames' wind tunnels still tied together its work in computational fluid dynamics at the start of aircraft design and automated flight testing at the end. Ames continued to invent new techniques to make more efficient use of its tunnels. With laser speckle velocimetry, for example, Ames solved the seemingly intractable problem of measuring unsteady fields in fluid flows. By seeding the air with microparticles, then illuminating it with a coherent light like that of a pulsed laser, they created speckled patterns which were superimposed on a photographic plate to create a specklegram. This specklegram recorded the entire two-dimensional velocity field with great spatial resolution. From this single measurement, aerodynamicists easily obtained the vorticity field generated by new aircraft designs. Similarly, Ames' fluid mechanics laboratory in 1987 started working closely with chemists at the University of Washington to develop pressure-sensitive paints that would turn luminescent depending on the amount of oxygen they

absorbed. The paint was easily sprayed on an aircraft surface before tunnel or flight testing and returned good data on the distribution of air pressure over the aircraft surface.

In addition to such upgrades in measurement equipment, Ames started upgrading what was still the world's best collection of wind tunnels. Ames had built many new special-purpose tunnels in the 1950s and 1960s, but many of the general purpose tunnels built in the 1940s had started to degrade. In 1967 NASA participated in a nationwide review of American wind-tunnels, and three at Ames were designated as being key national resources--the 40 by 80 foot, the 12 foot pressure, and the Unitary. (The vertical motion simulator and the arc jet complex were designated national resources in their categories.) Ames then planned a long-term effort to bring these tunnels up to the state of the art, and to keep all of its tunnels operating safely. Of these efforts, perhaps the most significant was the December 1987 rededication of the National Full-Scale Aerodynamics Complex (NFAC).

The 40 by 80 foot wind tunnel, the largest in the western world since its opening in 1944, remained Ames' most unrivalled tunnel. It had been in almost constant use, and had saved engineers from making countless design mistakes. Ames people expected that any funds invested in updating it would be returned many fold in better aircraft. For over a decade, Mark W. Kelly led groups from Ames to headquarters asking for funds for repowering the 40 by 80 foot tunnel and adding a new test section.

On 2 November 1978, Syvertson turned the first spade of dirt under the new 80 by 120 foot test section of the now renamed NFAC. (In addition to the one tunnel housing the two test sections, the complex also included Ames' outdoor aerodynamic research facility.) New drive motors capable of 135,000 horsepower--four times more powerful than the original motors--drove the need for new wood-composite fan blades and minor strengthening of the hull. The 40 by 80 foot section would continue to work as a closed-loop tunnel, with an air circuit a half mile long. The 80 by 120 foot tunnel would

be open at both ends, rather than closed loop, which reduced the cost to \$85 million and construction time to an additional six months. It would gulp in air through a horn-shaped inlet as big as a football field. Kenneth Mort, lead aerodynamicist on the upgrade, built a 1/50th scale model of the tunnel itself to show that Bay Area winds would not unacceptably degrade the smooth flow of the test air. This bigger section would operate at an airspeed only one-third that of the airspeed in the 40 by 80 foot test section, but was big enough for evaluating ever-larger military and commercial aircraft. Furthermore, the higher speed and larger size of the modified facility made it ideal for Ames' growing body of work in VTOL aircraft, helicopters, and aeroacoustics. The larger test section minimized tunnel-wall interference, which worsened at low speeds or when air was deflected downward and outward by rotorcraft. Since sound waves took some distance to propagate, large test sections were also important in aircraft noise studies, an issue becoming more politically sensitive. To make the new tunnel better suited to aeroacoustic research, and reduce the noise made while the tunnel was running, Ames engineers lined the test sections with six inches of sound-absorbing insulation. Cranes were added for moving around larger models. Better sensors, model mounts, wiring and computers were added for data collection. Construction of the composite tunnel ended in June 1982.

Just before noon on 9 December 1982--with only two months of shakedown tests to go before it would be fully operational--the NFAC suffered a serious accident. While running at 93 knots in the 80 by 120 foot test section, close to its maximum speed, a slip joint holding the hinge mechanism on vane set number 5 slipped. The entire lattice work of vanes broke up and its debris blew into the drive fans. Vane set 5 stood 90 feet high, 130 feet wide, and weighed 77 tons. Located 100 feet upwind of the fans, the nose sections of the vanes hinged to guide airflow around a 45 degree corner from the new 80 by 120 section into the old tunnel. All 90 fan blades, carefully handcrafted of laminated wood, were destroyed. The institutional trauma of

the accident announced itself with a terrifying thump heard around the Center. The accident affected morale throughout Ames though Syvertson assumed the blame that, as Center director, was ultimately his to bear. Ames had done a poor job supervising design and construction of the vane set. More stunning, Ames could no longer be proud of its safety record (though no one had been hurt in this accident). Syvertson had earlier nominated the Ames machine shop for a NASA group achievement award to recognize its year of no loss-time accidents. When NASA headquarters refused the nomination, on the grounds that NASA gave no awards for safety, Syvertson was so incensed that he refused the NASA Distinguished Service Medal that he was to be awarded.

Yet Ames wrested success from the tragedy. Ames tunnel managers shuffled the test schedule to make use of smaller tunnels, so that the accident added little to the two-year backlog of tests waiting for the tunnel to open. Ames estimated it would take one year and cost \$13 million to repair. However, a blue ribbon panel of aerospace experts convened by NASA and led by Robert Swain suggested taking this opportunity to make additional upgrades to boost the NFAC's reliability. This raised the total renovation cost to \$122.5 million, the amount Ames had originally requested. Better instrumentation, stronger structural steel, and turning vanes with sophisticated airfoils and no movable parts all created a more capable tunnel. New wiring for 1,250 channels pushed data at rates up to two million bits per second into computers where they could be instantly compared with theoretical predictions. Although both tunnels could not be run at the same time, engineers could set up tests in one tunnel while the other one ran. On 26 September 1986, the Ames project group led by Lee Stollar, started the first preliminary tests. Almost a year passed before the NFAC was declared fully operational.

Following the upgrade, airspeeds in the 40 by 80 foot test section could reach 345 miles per hour, the low cruise speed for many aircraft. The 80 by

120 foot tunnel, operating at 115 miles per hour, became the world's largest open-circuit tunnel. It proved especially useful in studies of actual aircraft and in situations where low-speed handling was especially critical, like during landing and take-off. It has been used to test a variety of aircraft on a large scale--fighter jets, lifting-body configurations, Space Shuttle models, supersonic transports, parachutes, and even trucks and highway signs.

Once Ames got the tunnel renovation program back on track after the accident, it focused on the 12 foot pressure tunnel. The tunnel hull had, since its opening in 1946, undergone constant expansion and contraction as it was pressurized to achieve its extraordinarily smooth flows of air and then depressurized. Such extensive, unrepairable cracks in the welds were discovered during a detailed inspection in December 1986, that Ames decided to rebuild the hull completely. Models of virtually every American commercial airliner had been tested in the 12 foot pressure tunnel, and aircraft designers hoped to continue to rely upon it. Beginning in 1990, a project team led by Nancy Bingham stripped and rebuilt the closed-loop pressure vessel, and installed an innovative air-lock system around the test section. The new air-lock let engineers enter the test section without depressurizing the entire tunnel, boosting its productivity and reducing the pressure cycling that had previously degraded the hull. Ames also integrated the new test and measurement equipment, and upgraded the fan drive. The 12 foot pressure tunnel reopened in November 1994, creating a superb test facility at a renovation cost of only \$115 million.

The 20 g centrifuge was built underneath the 40 by 80 foot tunnel in 1965 to test how well experiments flown in Biosatellite would survive the hypergravity of take-off and landing. By the early 1990s, it was one of six hypervelocity facilities at Ames, but the only human-rated centrifuge in NASA. "It's a simple facility," noted centrifuge director Jerry Mulenburg, "but it's very flexible for our purposes."³ Ames upgraded its controls and data collection system, completed in March 1994, and built a new treadmill cab to

fit on the end of its 58 foot diameter arm for exercise tests in it up to 12.5 g forces.

A major upgrade of the vertical motion simulator (VMS) was completed in May 1997, with construction of a new interchangeable cockpit. Ames built the new T cab in-house, specifically to satisfy the needs of NASA's tilt rotor and high-speed airliner programs. The new T cab had a side-by-side arrangement and an all-glass cockpit, so pilots could press easily altered touch-screens rather than actual instruments. The 270 degree view out the window was twice that of the other four cabs available to the simulator, which simulated helicopters, airplanes, and the Space Shuttle.

Since being placed in service in 1955, the Unitary Plan wind tunnel, like most Ames facilities, had been in almost constant operation. Such constant operation was planned, since Ames had designed the tunnel with massive diversion valves that allowed a test to be run in one section while models were set up in the other two. The drive system had accumulated over 70,000 hours of operation, as the Unitary complex tested every military aircraft, every significant commercial transport, and every manned spacecraft since its inception. The 11 foot transonic tunnel still had a 2.5 year backlog of tests, and the cost had risen to \$300,000 for a one-week test. Ames shut down the Unitary in 1996 for an \$85 million renovation to make it operate more efficiently. Modernization would automate the control system and improve flow quality in the transonic section by adding honeycomb flow straighteners, turbulence reduction screens, and segmented flaps in the wide-angle diffuser to eliminate flow separation. The Unitary modernization completed the overhaul of Ames most valuable physical assets and provided the research tools needed to continue moving aircraft concepts to flight tests--as it had with VTOL aircraft.

[Vertical Take-Off and Landing Aircraft]

The separation of lift from thrust (that is, using an airfoil and an engine instead of flapping wings) was the insight that made powered flight possible. Reuniting lift and thrust into propulsive lift, with the new technology earned over a half century of flight, promised a revolution in the relationship between aircraft and the populations they serve. Wing-tip rotors lift the aircraft like a helicopter, then the rotors tilt forward like propellers and transfer the lift from the rotors to the airfoil until the aircraft flew like an airplane. Helicopters do not fly forward efficiently. Fixed-wing aircraft find forward efficiency in higher wing loading, which requires longer runways, which then mandate bigger and more congested airports, farther from population centers. Tilt rotors can fly longer distances than helicopters, yet require little more space than a helipad to take-off and land.

Following World War II the Transcendental Company, a small American firm, built their Model 1-G tilt-rotor which flew 100 flights for a total of 23 hours. The Model 1-G was very small (1,750 pounds), never fully converted to full forward flight, and crashed in 1954 to the project. It proved the concept, but it did not end debate over which vertical take-off configuration minimized the weight penalty--that is, minimized the need for more powerful engines and stronger shafting that made propulsive-lift aircraft heavier than regular airplanes. So the U.S. Army let three contracts--to McDonnell Aircraft for the XV-1, to Sikorsky for the XV-2 stoppable rotor, and to Bell Aircraft Corporation for the XV-3.

Bell had started working on tilt rotors in 1944, and accelerated their research by hiring away from Transcendental the engineer Robert Lichten, who for the next two decades would be the dominant player in American tilt-rotor development. The XV-3 that Lichten and Bell designed for the U.S. Army was a small aircraft, only 5,000 pounds gross weight. A single engine mounted in the center turned a complex gear box system that powered large rotors at the tips of the wings.

The XV-3 first flew in 1955, and every flight was nerve-racking. The cockpit vibrated up and down whenever it hovered. To compensate for an engine simply too underpowered, Bell built the airframe too light. In a hover flight, in 1956, a rotor pylon coupling failed catastrophically and the pilot was severely injured. Bell strengthened the structure, thus restricting it to ground-tethered flights while they searched for solutions.

Following this crash, Ames engineers entered the picture in 1957, and started with some tests in the 40 by 80 foot wind tunnel. The XV-3 flew again in 1958, with NASA pilot Fred Drinkwater at the controls to define the conversion envelope between vertical and horizontal flight. Full conversion from helicopter mode to conventional forward flight was flown in August 1959, and the entire XV-3 test program proved a major advance in understanding the transition from ground to air. The XV-3 program ended in 1965 after a rotor pylon tore loose from the XV-3 while it was inside the 40 by 80 foot tunnel. For a few months, Ames and Bell engineers did a radical redesign of the remaining pylon to test ways to improve pylon stability--a major weak link in tilt rotor design. In 1966, Ames finally mothballed the XV-3.

AV-8B Harrier and VSTOL Handling Characteristics:

In the 1960s, though, the excitement over propulsive lift swirled around vectored-thrust jet aircraft. NASA contracted with British Aerospace to build the XV-6A Kestrel, which flew so well that it was quickly redesigned it into the Harrier, known in the United States as the AV-8B. The jet exhaust nozzle of the Harrier was pointed downward to lift it off the ground, then rotated backward to provide forward thrust. The Harrier's efficiency was poor when hovering, but it otherwise performed well in the marine fighter/attack role. Ames was fortunate to receive early prototypes of the Harrier, which they put in the 40 by 80 foot wind tunnel to gain a better understanding of the very complex airflows of vectored thrust.

Ames also used their flight tests with the AV-8B Harrier, as well as wind tunnel and simulator tests, to author handling qualities definitions for all future VSTOL aircraft (for vertical and short take-off and landing). VSTOL aircraft feel different to any pilot, whether they train on helicopters or fixed-wing aircraft. First published as a NASA technical note, these handling quality definitions were applied to all VSTOL aircraft in NATO and in the U.S. military through its VSTOL flying qualities specification.

But ideas for higher-efficiency propeller-driven VSTOL aircraft continued to percolate. NASA let contracts for a variety of approaches--like the Ryan XV-5A which used tip-turbine driven lift fans. For the U.S. Army, Vought (later LTV) built several XC-142 tilt-wing prototypes, which flew well but were very complex and had problems in conversion. Bell invested its own money, with considerable help from Ames, in designing its Bell Model 300. It had good hover and rotor efficiency and its pylons proved stable in 40 by 80 foot tunnel tests. Ames had worked hard, since the demise of the XV-3, to solve the lingering problems of tilt-rotor aerodynamics.

In 1970, NASA decided to fund another effort in tilt-rotor design. Foreign competitors were especially strong in small aircraft and helicopters, and NASA headquarters wanted America to regain the lead through a technological leap. In the debate that ensued, Gene Love and his colleagues at Langley favored a tilt-wing approach. But C.W. "Bill" Harper, then director of aeronautics at NASA headquarters, sided with his former colleagues at Ames in favoring the tilt-rotor approach.

XV-15 Tilt Rotor:

A key factor in Ames getting the XV-15 project was its close relationship with the Army Aviation Research and Development Laboratory, co-located at Ames since 1965. Because of this alliance with the Army, Ames had funds to refurbish an inactive 7 by 10 foot tunnel for small scale tests in advance of tests in the 40 by 80 foot tunnel. The complex aerodynamics of

helicopters and VTOL aircraft meant that they had to be tested in full-scale tunnels. On VSTOLs, effects could not be scaled, interference from downwash was extreme, and the hard work was in the details. The XV-15 was designed for medical evacuation and search and rescue missions that the U.S. Army had encountered during the war in Vietnam. The XV-15 had a gross weight of 15,000 pounds, a payload of 4,000 pounds, a cruising speed of 350 knots, and a range of 1,000 nautical miles--roughly twice that of the best helicopters. In 1970, management of the XV-15 went to a joint NASA-Army project office with David Few in charge. Half of the \$50 million required for the project came from Ames, half from the Army. Hans Mark gave it his full support. This was the first time Ames bought an aircraft meant to be a full-scale technology demonstrator--to show the military and airlines how easily they could build such an aircraft for regular service.

In September 1972, the Ames/Army project office gave both Bell and Boeing \$500,000 design contracts, and in April 1973 they declared Bell the winner. Led by program manager Ken Wernicke, Bell then apportioned the work for two XV-15 prototypes using standard components as much as possible. Rockwell fabricated the tail assemblies and fuselage, Avco-Lycoming modified a T-53 engine, Sperry Rand designed and built the avionics. Ames aerodynamicists immediately started modeling wind flows around the aircraft, for example, formulating equations to predict whirl flutter caused by a rigid rotor spinning on a pylon.

In exterior configuration, the XV-15 differed little from the XV-3. But as happens so often in aircraft development, better propulsion made the whole system remarkably better. The Lycoming turbine engines had much better power-to-weight ratios than those on the XV-3. Bell mounted one at each wing tip to turn the three-bladed proprotors, which were 25 feet in diameter. The only cross-shafting in the XV-15 was designed to carry load only when one engine failed.

The first XV-15 prototype rolled out of the hangar on 22 October 1976 for ground tests by Bell pilots. On 3 May 1977 Bell chief project pilot Ron Erhart first flew the XV-15: "It flew just like the simulator," wrote Erhart, "but with better visuals."⁴ On 23 March 1978, the XV-15 arrived at Ames for a more intensive series of flights. Ames pilots tested it in engine-out flight, and found the cross-shafting worked well in an emergency. On 24 July 1979, it made the full conversion from vertical to forward flight.

Ames discovered some fascinating aerodynamic problems. When the proprotors were tilted at certain angles relative to the wings, a large vortex was generated over each wing that caused strong buffeting in the tail. The only solution was to brace and stiffen the tail. Pilots found it took some time to get the feel of the conversion, and that it behaved oddly during taxiing and in light wind gusts.

In spring 1980 Ames opened its outdoor aerodynamic research facility (OARF), essentially a tilt-rotor tie-down facility on a hydraulic lift. By raising the wheel height from 2 to 50 feet off the ground (to accommodate the large proprotors) they could evaluate the XV-15 flying through air in any flight configuration. Ames aerodynamicists could measure rotor torque, fuel consumption, aircraft attitude, pilot control positions and--at various hover altitudes--ground effects, downwash, handling qualities, exhaust gas reingestion, zero wind force and moment data, and noise levels.

The XV-15 program was scientifically interdisciplinary--human factors, computing and digital controls all helped out in the crucial area of pilot workload. Flight data were cross-checked with tunnel data, which were matched to the formative efforts of computational fluid dynamics. The XV-15 culminated in an intense research program at Ames to further develop the VSTOL concept and to prove its commercial value and military utility. Yet it took some extraordinary steps to move the tilt rotor to its next iterations.

V-22 Osprey:

In 1978 Ames, emboldened by Hans Mark's duty as secretary of the Air Force, directly, and without success, tried to get the Army or Air Force to buy an improved tilt rotor for search and rescue missions. Mark made a special, and again unsuccessful, pitch to Admiral Holloway, former Chief of Naval Operations who led the investigation into the failed April 1980 effort to extract the American hostages from Iran. Resistance came because the U.S. Air Force had always fought its air wars from protected airfields, and thus saw no need for an operationally independent aircraft. And the Army already had expensive new helicopters entering service to fly those same missions.

Mark moved from the Pentagon to be deputy administrator of NASA early in 1981, and one of his first decisions was to take the XV-15 to the Paris Air Show. It was a hit. The new secretary of the Navy, John Lehmann, saw it at the show and became a staunch advocate of the tilt rotor. In 1982, NASA departed from usual practice and let its experimental aircraft be used in operational tests. The Army flew the XV-15 to simulate electromagnetic warfare near Fort Huachuca, Arizona. The Navy evaluated it aboard the U.S.S. Tripoli. P.X. Kelley, commandant of the Marine Corps, also became a tilt-rotor advocate, especially after the 1982 Argentine-British conflict over the Falkland Islands. Missiles used in the conflict showed that standoff distances between ships and a hostile shore had to be farther than the short operating ranges of ship-based helicopters allowed.

In 1983, the Marines issued the specification for what became the V-22 Osprey, a VTOL designed to replace the Boeing Vertol CH-46 and the Sikorsky CG-53 assault helicopters. Bell Helicopter Textron Inc. of Fort Worth teamed with Boeing Vertol of Philadelphia and won the contract in 1985. The V-22 was three times the size of the XV-15, with a total gross weight of 40,000 pounds, but otherwise similar. It would carry 24 heavily armed Marines from ship to shore in amphibious assaults. In a significant advance in airframe technology, many of the key structural members of the V-22 were made from fiber-reinforced graphite-epoxy laminate. The V-22 designers were

comfortable using composites so extensively because of the VTOL technology database developed at Ames, and overseen by John Zuk, Ames' chief of civil technology programs. The first V-22 flew on 19 March 1989, though it continued to work itself slowly into military service.

The success of the V-22 in military service should pave its way into civil transport, where it is most needed. Commuter airlines now flying small, propeller-driven Brazilian Embraers or European Fokkers may find that 40 seat tilt rotors, operating independent of congested airports, could move people much faster door-to-door. Ames led a study funded by the FAA, NASA, and DOD on the potential of the Osprey for civil transport, and the New York Port Authority asked Ames to help explore the potential of tilt rotors to solve local transportation problems.

[Jet-STOL Aircraft]

Ask pilots, and they'll say that just as important as flying fast, is being able to fly slowly well. Slow-speed flight remained out of fashion as engineers built aircraft to go faster and farther, but Ames researchers always held a great deal of respect for complex airflows at slow speeds. So Ames developed expertise in the aerodynamics of slow-speed flight in order to help in the design of aircraft that handled better in the trickiest parts of any flight--takeoff and landing. Better performance at slow speeds also resulted in aircraft that could takeoff or land on much shorter runways--important for commuter airlines operating from smaller regional airports or for military pilots operating from unimproved foreign airfields.

Thus, in conjunction with researchers from the U.S. Army, Ames used its expertise to build a series of STOL aircraft (for short takeoff and landing) like the augmented-wing quiet short-haul research aircraft (QSRA), the rotor systems research aircraft (RSRA), and the E-7 short takeoff and vertical lander (STOVL) test model.

Augmentor Wing STOL, Quiet Short-Haul Research Aircraft:

Ames first worked to develop specific technologies that airframe companies could apply to other short takeoff and landing aircraft. A rotating cylinder flap, for example, improved lift by energizing boundary layers as it turned airflow downward over the trailing edge of the wing. Ames installed a rotating cylinder flap on a OV-10 Bronco and, even though radically modified, the OV-10 proved the point faster and cheaper than building a completely new technology demonstrator. Ames shortened the wings, removed the flaps and pneumatic boundary-layer control, shortened the propellers, boosted the gross weight from 8,500 to 11,500 pounds to get rotation to the cylinders, and cross-shafted the two engines for better performance at slow speeds. Before its first flight in August 1971, Ames completely tested the OV-10 in the 40 by 80 foot tunnel. The rotating cylinder used so little power that full horsepower was available for takeoff. Compared with the basic OV-10, it achieved 33 percent better lift.

In the 1970s, Ames and Canadian researchers joined to study jet-STOL with a complete flying test bed. They modified a government surplus deHavilland C-8 Buffalo turboprop aircraft to demonstrate the technology of powered-lift ejector augmentation. The modified Buffalo first flew on 1 May 1971 and remained at Ames in flight tests through 1976. Its thrust-augmentor wing achieved augmentor ratios of 1.2 with significant gains in lifting coefficients, so that it could fly as slow as 50 knots and approach the landing field at 60 knots. It routinely demonstrated takeoffs and landings in less than 1,000 feet, with ground rolls less than 350 feet. After a full range of technical flight tests, Ames pilots flew the Buffalo in a series of joint flights--with the FAA and the Canadian department of transportation--to develop certification criteria for all future powered-lift aircraft.

Ames' next iteration of powered-lift aircraft was the QSRA (for quiet short haul research aircraft). Boeing of Seattle built the QSRA from the C-8 Buffalo and four spare Lycoming turbofan engines. The engines were

mounted on top of the wing, so that the exhaust air blew over the upper surface, creating more lift, while the wing shielded the noise from the ground below. The QSRA wing was also entirely new, emulating a supercritical airfoil capable of Mach 0.74 (though the QSRA never went that fast) and a wing loading of 80 pounds per square foot. The result was a very quiet, efficient aircraft, capable of very short takeoffs and landings.

Boeing delivered the QSRA to Ames in August 1978, and it quickly validated the concept of upper-surface blowing. The QSRA could fly an approach at only sixty knots, at a steep, twenty-degree angle. "It feels as if it's coming down like an elevator," said Jim Martin, QSRA chief test pilot.⁵ During carrier trials in July 1980 aboard the USS Kitty Hawk, with wind over the deck at thirty knots, the QSRA took off in less than 300 feet and landed in less than 200. In zero-wind conditions, during Air Force tests to simulate operations on bombed runways, the QSRA took off in less than 700 feet and landed in less than 800 without thrust reversers. The real military payoff, however, was that augmented lift boosted payload capacity by 25 percent. In 1983, Jim Martin and Robert Innis flew the QSRA to the Paris Air Show to encourage companies to use the technology in commuter aircraft. Short takeoffs and landings were important to operating bigger aircraft on smaller, local runways; more important, the QSRA far surpassed federal requirements for noise abatement. It flew a demonstration landing into the Monterey, California, airport completely undetected by the airport monitoring microphones.

Over the fifteen years that Ames pilots flew the QSRA, they conducted 697 hours of flight tests which included more than 4,000 landings--averaging nearly six landings per flight hour. More than 200 research reports emerged from data collected on the QSRA. Once the aircraft itself was understood, the Ames QSRA team, led by John Cochran and then Dennis Riddle, used it more as a test bed for new technologies. The renamed NASA Powered-Lift Flight Research Facility provided an ideal platform, beginning in November 1990, to

test a jump-strut nose gear that kicked up an aircraft nose during takeoff. Ames retired the QSRA in March 1994.

Rotor Systems Research Aircraft:

Another unusual aircraft that bridged the worlds of vertical and fixed-wing flight was the rotor systems research aircraft (RSRA). Sikorsky built two RSRAs, originally for research at Langley, that arrived at Ames in September 1979. A NASA/Army team designed them as flying wind tunnels--highly instrumented, flying test beds for new rotor concepts. One was built in a helicopter configuration, powered by two T-58-GE-5 turboshaft engines with an S-61 main transmission. The second had a compound configuration, meaning it could fly with lift provided by two short wings as well as by the helicopter rotor. Two TF-34-GE-400A turbofans were added as auxiliary engines, and the aircraft was instrumented to measure main and tail rotor thrusts and wing lift. Warren Hall served as RSRA project pilot.

The helicopter RSRA was later modified to test an X-wing configuration proposed by the Defense Advance Research Projects Agency (DARPA). The X-wing RSRA had a single four-blade rotor, built out of composite materials, that lifted the aircraft vertically like a helicopter. Air blown through a fore or aft strip along each rotor blade provided pitch and roll control. As its turbojet engines thrust it forward as fast as Mach 0.8, the rotor provided lift as a symmetrical airfoil with a four-blade X shape. The convertible engine divided its power as it shifted between rotor flight and jet exhaust. In aircraft mode, the air blown through the rotor blades provided lift and control. The RSRA flew only three times in the X-wing configuration, before being abandoned as too difficult to control.

Rotary Wing Aircraft:

Ames began working on rotorcraft in the early 1970s as its research relationship with the Army aeroflightdynamics directorate expanded.

Initially, studies focused on pilot control during terminal operations--getting aircraft on and off the ground, especially during bad weather--and Ames built a sophisticated series of flight simulators for helicopter pilots.

Ames' inventory of rotorcraft jumped in the late 1970s, when five other helicopters were transferred to Ames from Langley: the UH-1H and AH-1G for rotor experiments, and the SH-3 and CH-47 for operational studies. Ames established a new helicopter technology division to focus on these aircraft, to pursue research in rotor aerodynamics and rotor noise, and to develop new helicopter technologies. The Army, likewise, continued to beef up the technical expertise in its Aeromechanics Laboratory, led by Irving Statler. Ames and Army aerodynamicists developed a free-tip rotor, for example, with a tip that was free to pitch about its own axis, which was forward of the aerodynamic center. Ames built a model that showed that the free-tip rotor reduced power at cruise speed, minimized vibratory flight loads, and boosted lift by sixteen percent.

Ames flew the UH-1H to develop automatic controls for landing a helicopter, culminating in a fully-automatic digital flight guidance system known as V/STOLAND. Principal engineers George Xenakis and John D. Foster first developed a database of navigation and control concepts for instrumented flight operations. Kalman filtering extracted helicopter position and speeds from ground-based and onboard sensors. To define the helicopter's approach profile and segregate it from other airport operations, the system investigated several helical descending flightpaths. Lloyd Corliss then led a series of UH-1H test flights on flying qualities for nap of the earth operations. Victor Lebacqz used it to devise certification criteria for civil helicopter operations. Later, project pilots Dan Dugan and Ron Gerdes flew the UH-1H in the first demonstration of automatic control laws based on the nonlinear inverse method of George Meyer.

The Bell AH-1G White Cobra arrived and was highly instrumented for the tip aerodynamics and acoustics test (TAAT) to establish better prediction

methods for this type of twin-blade rotor. Ames got the highly-instrumented rotor blades that the Army had used for its operational loads survey, and added additional absolute pressure instrumentation to the rotor tips. Thus, one rotor blade returned 188 pressure transducer measurements, with 126 more measurements added by the other blade and the rotor hub. Robert Merrill was chief pilot and Gerald Shockey led the project, which returned detailed measurements of aerodynamics, performance, and acoustics.

Ames modified the CH-47B Chinook to include two digital flight computers, a programmable force-feel system, and a color cathode-ray tube display. This system allowed wide variations in the helicopter's response to pilot controls, making it an ideal variable-stability research helicopter. Ames used it in flight simulations to define new military handling qualities. In close cooperation with Stanford University researchers, Michelle Eshow and Jeffery Schroeder used the CH-47B to investigate multiple input and output control laws developed on Ames' vertical motion simulator. The Army let Ames use the CH-47B from 1986 until September 1989, just before they closed out the line that remanufactured them into a CH-47D suitable for Army duty.

To carry forward this variable-stability research, in 1989 Ames acquired a Sikorsky JUH-60A Black Hawk. Known as RASCAL (for rotorcraft aircrew systems concepts airborne laboratory), it carried extensive vehicle and rotor instrumentation, a powerful 32-bit flight control computer, and image generators for the cockpit. "We're putting a research laboratory in a helicopter," said RASCAL program manager Edwin Aiken. "Now when we experiment with flight control software, advanced displays or navigation aids, we can get a realistic sense of how they work."⁶ Ames and Army engineers used RASCAL to develop a range of new technologies--active sensors like millimeter wave radar, passive sensors using infrared, and symbologies for advanced displays. The goal was to make helicopters respond to pilot controls with more precision and agility, to provide better obstacle avoidance and automated maneuvering close to the terrain, and to improve vehicle stability

when carrying loads or using weapons. For example, Ernest Moralez helped devise algorithms that would automatically protect a flight envelope in which pilots could then maneuver freely.

Another UH-60 Black Hawk also entered the Ames inventory in September 1988 as part of the modern rotor aerodynamic limits survey (MRALS). Sikorsky Aircraft built two highly instrumented blades for the Ames/Army program. A pressure blade with 242 absolute pressure transducers measured airloads--the upward force produced as the blades turn. A strain-gauge blade with a suite of strain gauges and accelerometers measured the structural responses to air loads. The pressure blade alone returned a 7.5 megabit data stream, which demanded a bandwidth well beyond the state of the art. An Ames group, led by Robert Krufeld and William Bousman, devised a transfer system that returned thirty gigabytes of data during test flights in 1993 and 1994--data then archived onto optical laser disks in a jukebox storage system for immediate access via modem by rotorcraft designers. The UH-60 studies ended a ten-year airloads program, launched in 1984 and completed for only \$6 million. Its legacy was an airloads database actively used to refine helicopter design and to better predict performance, efficiency, airflows, vibration, and noise.

By taking novel technical approaches to first isolating and then solving seemingly intractable problems, and integrating their use of computation, tunnel, and flight testing, Ames bolstered the core technologies found in all helicopters. Ames people made similar contributions to the Space Shuttle program. While other NASA Centers led systems design, integration and management, Ames tackled the tough issues of aerodynamic configuration and thermal protection.

]Space Shuttle Technology[

In 1971, Ames established a small Space Shuttle development office to coordinate all the people at the Center who were working on Shuttle

technologies. Using the NFAC, the Unitary, and 3.5 foot hypervelocity tunnels, Ames did half of all wind-tunnel tests--to increasing speeds--during the crucial phase B of the Shuttle design. Ames people used the expertise earned in lifting-body studies to refine the Shuttle configuration, and expertise earned in digital fly-by-wire to design controls for the Shuttle. Shuttle trainees spent fifty weeks in the Ames vertical motion simulator studying handling qualities during landing. Furthermore, Ames managed NASA's Dryden facility which served as the primary test facility and landing site for all early Shuttle flights. Despite the magnitude of these efforts, Ames worked on Shuttle technologies, as it had on Apollo technologies, without having the program dominate the mission of the Center. And as with Apollo, Ames' primary contribution was solving the problems of hypersonics and materials that got the Shuttle astronauts home.

When the Space Shuttle orbiter Columbia first touched down at Ames-Dryden in April 1981, shuttle commander John Young exited the orbiter, walked underneath, looked around, gave a thumbs up, then jumped with joy. The thermal protection system was the key to making the Space Shuttle the world's first reusable reentry vehicle. Heatshields used earlier on Apollo and other single-use capsules had been rigid, with ablative materials designed to burn up while entering the atmosphere only once. The airframe of the Shuttle Orbiter, however, would be flexible like an aircraft, with complex curves, and had to be built from a system of materials that rejected heat without ablating. Once NASA had decided, in the mid-1960s, on reusable insulation for the Shuttle orbiter, the airframe firms that hoped to build it started showing up at Ames for advice and tests.

Howard Larson took over Ames' thermal protection branch in 1968. Larson had spent most of the 1960s studying how ablation changed the shape of bodies that entered Earth's atmosphere--like meteors, ballistic missiles, and capsules--and thus affected their aerodynamic stability. Nonablative thermal protection, however, required an entirely new class of heat shield materials.

To help evaluate these, in 1970 Larson hired Howard Goldstein, a thermodynamicist and materials scientist then running arc jet tests at Ames for a NASA contractor. As the pace of materials testing accelerated the Shuttle contractors increasingly bumped up against the size and run-time limitations of Ames' 20 megawatt arc jet. But Ames still had the largest direct-current power source in NASA, as well an enormous infrastructure for compressing atmospheres. In 1971 Dean Chapman, who as director of astronautics oversaw Larson's work, secured funds to build a 60 megawatt arc jet. Materials science quickly took on new prominence at Ames.

In 1971 Ames directed its efforts to help Johnson Spaceflight Center evaluate a new class of reusable surface insulation for the Shuttle. Lockheed Missiles and Space had developed tiles based on low-density rigid silica fiber--called the LI-900 tile system--that was selected in 1973 cover two-thirds of the Shuttle's surface. Goldstein led Ames' effort to apply the data base built during arc jet tests of this and other candidate materials to develop improved heat shields. An early Ames product was a black borosilicate coating, called reaction-cured glass (RCG), that provided a light-weight and easily manufactured surface for the underlying silica tiles. In 1975 RCG was adopted for use over 75 percent of the orbiter surface. Ames also developed the LI-2200 tile, which was stronger and more refractory. This new tile, adopted in 1976, replaced ten percent of the tiles on the orbiter Columbia.

When the 60 megawatt arc jet came on line, in March 1975, Ames could test full-scale tile panels in flows running thirty minutes, which is twice as long as the Shuttle reentry time. Ames performed most of the arc jet runs to certify the Shuttle thermal protection system, often running two shifts to fully simulate the Shuttle's 100 flight lifetime. From this, Ames scientists gained new insight into the aerodynamic heating resulting from plasma flow over complex heat shields. When Shuttle designers grew concerned about hot-gas flows between tiles, the Ames thermal protection branch devised a gap filler--a ceramic cloth impregnated with a silicone

polymer. Once adopted in 1981, few Ames gap fillers have ever had to be replaced.

NASA also hoped to replace the white tiles that covered the top surface of the Shuttle orbiters (called LRSI for low-temperature reusable surface insulation) with a material that was cheaper, lighter, less fragile, and easier to maintain. So Ames worked with Johns Manville to devise a flexible silica blanket insulation (called AFRSI for advanced, flexible, reusable, surface insulation). Beginning in 1978, the AFRSI replaced most of the white tiles on the four later Shuttle orbiters. As the orbiters extended their operational lives, Ames researchers continued to invent and test improved reusable surface insulation tiles. Ames devised new family of materials, which led to an even stronger and lower-weight tile system called FRCI-12 (for fibrous refractory composite insulation) which was adopted in 1981 to replace ten percent of the tile system. The insulation for the Shuttles has turned out to be lighter and easier to refurbish than previously expected, and has provided an excellent technical base on which to build the heat-shielding for all future hypersonic vehicles.

Into the 1990s, led by Daniel Leiser and Daniel Rasky and guided by James Arnold, Ames continued to develop new thermal protection systems. David Stewart led Ames' basic research in catalysis--the study of how nitrogen and oxygen decompose in a shock then reform on a heatshield with lots of energy release--and made catalytic efficiency the basic measure for evaluating new insulators. An April 1994 mission with the shuttle Endeavor allowed the Ames thermal protection materials branch to test out a new material called TUF1 (for toughened uni-piece fibrous insulation) which is more resistant to impact damage from the dirt kicked up as the shuttle lands. Another new tile, called AETB for alumina enhanced thermal barrier, was adopted to replace tiles as the Shuttle further extends its operational life into the new century.

A new class of hypersonic vehicles and reusable launch vehicles under development in the late 1990s--such as the X-33, the X-34, the X-38, and the Kistler K-1--all depend upon Ames' work in thermal protection. Jeff Bull, Daniel Rasky, and Paul Kolodziej of Ames also developed SHARP technology--a very high temperature ceramic that will finally allow reentry vehicles to have a pointy leading edge rather than a blunt shape. In addition, Huy Tran led a team developing a silicon-ceramic heatshield for the Mars Pathfinder and a phenolic-carbon ablating heatshield for the Star Dust asteroid return mission and the Mars sample return mission.

]Planetary Science[

The study of planetary atmospheres became a natural area of inquiry for Ames, since it merged work in the life sciences, atmosphere entry, aerodynamics and instrumentation with efficient project management. During the Apollo years Ames had begun work in space science. Donald Gault had used Ames vertical gas gun to study cratering and meteoritics, information needed then for picking lunar landing spots. This information then grew in importance as scientists learned more about the role of impacts in the evolution of all planets. Charles Sonett led work on magnetometers, and John Wolfe, Vernon Rossow, and John Spreiter did work on solar plasmas. Carr Neel, John Dimeff and others in Ames' instrumentation branch built the sensors. When better satellites travelled beyond the magnetosphere, Ray Reynolds led efforts to expand the Ames space sciences division to keep abreast of the data coming in. By the mid-1970s, a space science renaissance was born of the incredible diversity of data being returned--from the Pioneers to Jupiter and Saturn, Earth observation aircraft, the Viking lander, and the atmospheric probes. Years of planning and calibration culminated in a flurry of spectacular results from probes Ames had sent all over the solar system.

In the mid-1960s, Alvin Seiff and David Reese began to explore the idea that a probe entering the atmosphere of a planet could determine the atmosphere's structure (density, pressure, and temperature variation) as well as its composition. This idea emerged as Ames' vehicle environments division first considered the problems of a landing a human mission on Mars through its still unknown atmosphere. Since the probe would enter at very high speed, and perhaps burn up, it could carry no direct-measuring sensors. Accelerometers, instead, would measure changes in the air speeds which aerodynamicists used to compute changes in density and atmospheric pressure. Temperature yielded information on the molecular weight of the atmosphere, so long as the aerodynamics of the probe were calibrated in the Ames tunnels over a variety of Mach and Reynolds numbers and in a variety of gases. The idea was intriguing to a great many aerodynamicists at Ames, who were accustomed to defining an atmosphere then designing an aircraft configuration to produce the aerodynamic performance they wanted. Seiff turned the problem on its head--defining the configuration and performance to understand the atmosphere. Work began immediately in the hypersonic free flight facility, and with probe models dropped from aircraft.

The precursor to all of Ames' work in planetary probes was the June 1971 planetary atmosphere experiments test (PAET). PAET used what Ames had learned about reentry and hypersonics to push the frontiers of planetary studies. PAET was a complete prototype of the planetary probes to follow. It carried accelerometers, pressure and temperature sensors, two instruments to measure the composition of earth's atmosphere, a mass spectrometer and a shock layer radiometer. A Scout rocket launched from Wallops Station boosted the PAET out of Earth's atmosphere. A third stage rotated it back toward Earth, and a fourth rocket stage shot it into the atmosphere at 15,000 miles per hour. The data it returned validated the concept of the atmosphere entry probe and--after scientists found an almost perfect match between PAET data and conventional meteorological data on atmospheric conditions. This

provided the confidence to build probes to survey the atmospheres of other planets.

The two Viking landers that settled down on the surface of Mars in September 1976 carried an atmosphere structure experiment designed by Seiff. Though not a probe, it provided the first detailed sounding of the structure of the Martian atmosphere. The Viking landers also included what would be Ames' first astrobiology experiment--a life detection experiment built by the Ames life sciences division, led by Chuck Klein. After Earth, Mars is the most likely planet in our solar system to support life. To search for such life, Vance Oyama built a gas-exchange laboratory around a gas chromatograph to measure gas respiration in the Martian soil as it was treated with biological nutrients. It was a complex design: an arm extended to collect a sample, drop it in a jar, mix it with chemicals, and define the resultant gas. The gas-exchange experiment worked flawlessly, and displayed the highly reactive chemical structure of the Martian soil. It found no evidence of life, though questions about what it did find motivated planetary scientists for years to come.

Pioneer Venus:

The Pioneer Venus program was initiated in the same spirit as the earlier generations of Pioneer spacecraft--as a faster, better, and cheaper way of generating data about the atmosphere of Venus. It was managed by many of the same team, on the same management principles, with the same thirty month schedule, an equally conservative approach to engineering, and a simple set of "rules of the road for Pioneer Venus investigators" that kept the science paramount and focused. The mission to Venus earlier had been proposed to NASA by two atmosphere scientists--Richard Goody of Harvard University and Donald Hunten of the University of Arizona. Based largely on the spectacular results of the PAET, NASA headquarters cancelled the Planetary Explorer program from Goddard, in January 1972, and opened in its

place a Pioneer Venus group at Ames. Charles Hall led the group as Pioneer project manager, and Hughes Aircraft built the spacecraft. Among the experiments selected competitively to be included on the probes were those devised by four Ames researchers: Alvin Seiff on atmosphere structure, Vance Oyama on atmosphere composition, Boris Ragent on cloud detection and Robert Boese on radiative seposition.

The Pioneer Venus spacecraft had two components: an orbiter (Pioneer 12) that carried scientific instruments and a multiprobe bus (Pioneer 13) that launched the four probes into the atmosphere. The orbiter was launched on 20 May 1978; the multiprobe on 8 August. By 4 December the orbiter was in place and, five days later, the probes were dropped. Together, they returned data on the most thorough survey of another planet ever made.

Ames built each probe to known aerodynamic parameters so that its motion in flight, at an initial speed of 26,100 miles per hour, indicated the density of the atmosphere through which it travelled. As the probes heated up and interacted chemically with the atmosphere, they relayed data back to Earth on the climate, chemical makeup, and the complicated structure of the Venusian atmosphere. The Pioneer Venus science team found, for example, that there were remarkably small temperature differences below the clouds compared with the differences above, that the solar wind shapes Venus' ionosphere, and that the wavelike patterns visible from Earth are in fact strong wind patterns. They quantified the runaway greenhouse effect that makes the planet surface very hot. They identified widely varying wind speeds in the three major layers of clouds and a layer of smog, nine miles thick, atop the clouds. Using technology developed for the Viking gas exchange experiment, the Pioneer Venus Orbiter first discovered the caustic nature of the Venusian atmosphere. They found that the surface was incredibly dry, and described the chemical process by which Venus' hydrogen blew off and its oxygen absorbed into surface rocks. They also measured its electrical activity, looking for evidence of lightning. Using these data and

data returned from the Soviet Venera spacecraft, Ames scientists--James Pollack, James Kasting, and Tom Ackerman--proposed new theories of the origins of Venus' extreme atmosphere.

With the orbiter's precision radar, the Pioneer Venus team drew the first topographic maps of the cloud-enshrouded Venusian surface. They discovered that Venus had no magnetic field, from which they deduced that Venus had no solidifying core. They further discovered that Venus lacked the horizontal plate tectonics that dominated Earth's surface geology.

Early in 1986, Ames mission controllers reoriented Pioneer Venus, still in orbit around Venus, to observe Comet Halley. It was the only spacecraft in position to observe the comet at its most spectacular--at perihelion, where it comes closest to the sun and is most active. With Pioneer's ultraviolet spectrometer pointed at Halley, Ames scientists gathered data on the comet's gas composition, water vaporization rate, and gas-to-dust ratio. Five more times, mission controllers at Ames reoriented the Pioneer Orbiter to observe passing comets.

The Pioneer Venus orbiter continued to circle the planet, working perfectly, for fourteen years--over one full cycle of solar activity. Its mission ended in October 1992, when controllers directed it into ever-closer orbits until it finally burned up. In doing so, it returned the best data yet supporting the theory that Venus was once very wet. For a cost averaging \$5 million per year over its fourteen year mission, Pioneer Venus generated a wealth of good science. By 1994, more than a thousand scientific papers had been written from Pioneer Venus data, authored by scientists from 34 universities, 14 federal laboratories, and 15 industrial laboratories. While planetary scientists continued mining Pioneer Venus data, the Ames people who built it turned their expertise to building similar probes for the atmospheres of Mars and Jupiter.

Galileo Jupiter Probe:

Jupiter's atmosphere presented by far the biggest challenge for Ames planetary probe builders. Jupiter's huge gravity will accelerate a probe more than five times faster than the gravitational pull of the inner planets. Jupiter's enormous thermal and radiation energy and violent cloud layers are ominous spacecraft hazards. Jupiter has no recognizable surface; its deep atmosphere just gets denser and hotter until the edge blurs between atmosphere and any solid interior. Ames scientists expected any Jupiter probe to encounter 100 times the heat of an Apollo reentry capsule--something like a small nuclear explosion.

Ames managed the Galileo Probe project, and Hughes Aircraft of El Segundo built it. Robert Boese developed a net flux radiometer, Boris Ragent developed a nephelometer to measure the scatterings of cloud particles, James Pollack and David Atkinson devised a Doppler winds experiment, and Al Seiff led the probe atmosphere structure experiment--measuring pressure, temperature and density--culminating work he began in the late 1950s on the use of entry probes to define planetary atmospheres. Ames built a unique outer planets arc jet, led by Howard Stine and James Jedlicka, to simulate the most caustic and stressful atmosphere a man-made material would ever encounter. After computing and testing various exotic materials for their ability to withstand the heat, shocks, and spallation from the Jovian atmosphere, Ames chose carbon phenolic from which to engineer the massive heat shield needed to protect the probe as it entered the Jupiter's atmosphere.

Hughes delivered the probe on schedule in February 1984, expecting an encounter in May 1988. Then it sat in storage for eight years. Galileo was designed to be launched from the bay of the Space Shuttle orbiter, but the Challenger accident threw the launch schedule into turmoil. In January 1988 NASA sent Galileo, now eight years old, back to Hughes for refurbishment and performance checks. Galileo was finally launched in October 1989, with a less powerful upper stage rocket and a more convoluted flight plan--one

taking it by Venus and Earth to pick up speed on its journey toward Jupiter. Between design and launch, Benny Chin had taken over as probe project manager from Joel Sperans, Richard Young had taken over as project scientist from Larry Colin, and John Givens arrived as probe development manager.

After travelling six years and 2.5 billion miles to Jupiter with the Galileo Orbiter, the probe separated and entered Jupiter's atmosphere on 7 December 1995. The probe slammed into the atmosphere travelling 115,000 miles per hour, with deceleration forces 350 times Earth gravity. The incandescent gas cap ahead of the heat shield reached 28,000 degrees Fahrenheit, meaning to an observer on Jupiter it glowed as bright as the sun. Almost half of the probe mass was heat shield, most of which ablated away and the remainder of which fell away as the parachute deployed to slow its descent.

Seven instruments sent data back to the Galileo Orbiter where it was stored for relay to the Jet Propulsion Laboratory. But soon after the encounter, the Galileo Orbiter went over the horizon, then followed Jupiter behind the sun, clouding the radio signal with noise. Scientists had to wait three long months for the complete return of data. Data received the following spring confirmed that in the hour before it went dead under the pressure of the atmosphere, the Galileo Probe returned the first direct measurements of the chemical composition and physical structure of Jupiter's clouds. The probe entered a hotspot--a gap in the clouds where the atmosphere was dry and deficient in ammonia and hydrogen sulfide. The probe survived to a depth of 22 atmospheres, sending data on atmospheric conditions and dynamics the whole way in.

Airborne Sciences:

Meanwhile, Ames scientists studied Earth's atmosphere with equal fervor. Ames rebuilt its on-Center fleet of aircraft and outfitted them as flying laboratories used to conduct research in airborne science and Earth

observation. Ames' medium-altitude aircraft included a Learjet, a Convair 990 named Galileo II, and a Lockheed C-130.

The Learjet, though most often used for infrared astronomy, also proved useful in atmospheric studies of low-altitude wind shear in the 1970s. The Lockheed C-130 focused on Earth resources--in support of agriculture, meteorology, and geology--and carried sophisticated equipment for mapping cropland, soils, and nonrenewable resources. The C-130, equipped with a thermal infrared mapping sensor, was often called into service throughout the western United States to locate hot spots obscured by the dense smoke over forest fires. (And Ames researchers, ever interested in applying all their expertise to solving problems, in 1994 developed a low-cost electronic chart display to coordinate the many aircraft navigating around such large fires.) George Alger of Ames' medium altitude missions branch led the C-130 in a variety of meteorology missions looking, for example, at biogeochemical cycling--how land interacts with the atmosphere.

Galileo II was the fastest aircraft in the fleet, and accommodated international teams of 35 researchers. This made it especially valuable for global atmospheric research. Observers aboard Galileo II explored the origins of monsoons in India, interactions between ice, ocean and atmosphere off the northern coast of Greenland, and global atmospheric effects from the eruption of the Mexican volcano *el Chicon*. In 1990, Galileo II flew a research team led by Charles Duller that verified the discovery of a crater rim along the Yucatan peninsula. This provided evidence for a cometary or asteroid impact on Earth that might have led to the extinction of the dinosaurs.

Ames' first high-altitude aircraft, capable of flying to 70,000 feet, were two Lockheed U-2Cs that arrived in June 1971. As with so many research tools acquired during Mark's tenure as director, the U-2s were grabbed as surplus from another agency. The U.S. Air Force had announced that it would make the U-2s available for basic research. NASA was then in final preparations for the earth resources technology satellite (ERTS), managed by

Goddard, and scientists were concerned that infrared and spectral-band photographs obtained on ERTS might be distorted because they would be taken through the entirety of Earth's atmosphere. The Air Force tasked Martin Knutson, one of the first U-2 pilots, to evaluate Ames' ability to fly and maintain the U-2s, which were notoriously slender and sensitive aircraft. Knutson then retired from the Air Force and joined Ames' airborne sciences office to lead the Earth Resources Aircraft Project to simulate the data collection process from the ERTS satellite. When delays meant the ERTS would miss its opportunity to survey chlorophyll levels in American crops during the summer 1972 growing season, Ames leapt to a plan and with three months of flights completed the entire benchmark survey with the U-2s. From there, research uses for the U-2s branched in many directions. In 1972, NASA headquarters designated Ames its lead center in Earth-observation aircraft and as a liaison to the scientific community. In response, Ames established an atmospheric experiments branch.

In June 1981, the U-2s were joined by a Lockheed ER-2 (for earth resources), a civilian version of the U-2. In May 1988 Ames acquired a second ER-2, and retiring its thirty year old U-2C. (Before being retired to static display at an Air Force base, this U-2C shattered sixteen world aviation records at Dryden for time-to-climb and altitude in horizontal flight, to 73,700 feet. These records were the first official acknowledgment of the U-2's previously classified altitude capability.) NASA and Lockheed Martin would later share a Collier trophy for development of the ER-2. Compared with the U-2, the ER-2 was thirty percent larger, carried twice the payload, had a range of 3,000 miles, had a flight duration of eight hours, and had four pressurized modular experiment compartments. In addition, Ames modified a DC-8 airliner into a flying laboratory for Earth and atmospheric sensing and for other key roles in NASA's Mission to Planet Earth. Ames often teamed the DC-8 and ER-2s on specific projects.

Ames scheduled the ER-2s flexibly enough, and built basing alliances with 42 airports around the world, so that Ames pilots could use them for quick-response storm observation, atmospheric sampling, and disaster assessment. The Ames U-2 measured ash cloud dispersement following the May 1980 eruption of Mount Saint Helens in Washington state. Life scientists at Ames and the University of California at Davis used remote-sensing data on vegetation growth, collected between 1984 and 1988, to devise a model that actually predicted the spread of mosquitos that carried malaria. Similar remote spectral scanners were used in April 1993 for Project GRAPES, an effort to plot the spread of phylloxera infestation through California vineyards. The ER-2s proved especially useful in calibrating new remote-sensing equipment flown aboard LANDSAT Earth-observation satellites and the Space Shuttle. In 1989 and 1990, the DC-8 flew the global backscatter experiment (GLOBE) to survey airborne aerosols in the Pacific basin and test out new experiment packages designed for the Earth Observing System satellite. In February 1993, Rudolf Pueschel and Francisco Valero of the Ames atmospheric physics branch led the DC-8 and an ER-2 to Australia to map the interior of a tropical cyclone and explore the coupling of the atmosphere and the warm ocean.

Perhaps the most significant research done by Ames' airborne scientists was the many-year exploration of Earth's ozone layer. In August and September 1987, operating from Punta Arenas at the southern tip of Chile, Ames scientists used the ER-2 and the DC-8 to make the first measurements that implicated human-made materials in the destruction of stratospheric ozone over Antarctica. During the winter of 1989, the ER-2 and DC-8 team, led by Estelle Condon and Brian Toon and based in Norway, completed an airborne campaign to study ozone chemistry and distribution over the Arctic. The ER-2 and DC-8 returned to the Arctic in 1992 to map changes in stratospheric ozone, and the results of their work were written into the Montreal Accord on limiting chemicals that deplete the ozone.

Infrared Astronomy:

The other airborne platforms in Ames' fleet played a key role in the growth of the discipline of infrared astronomy. Until the 1960s, the main reason telescopes were mounted on airplanes was to follow solar eclipses. But the invention, in 1961, of a germanium bolometer able to detect infrared radiation up to 1,000 microns in wavelength opened up the age of infrared astronomy.

The ancients gazed into the night sky and saw a majestic canopy of changeless stars. Optical telescopes and spectrographs of great power further unveiled the immensity and complexity of the universe but always within a small window--wavelengths that were both visible and that made their way through Earth's atmosphere. Aircraft, then spacecraft, let astronomers place their instruments far above the obscuring water vapor of the atmosphere where they could see all the messages that the universe was sending us--all the radiation, from all the sources, at all the wavelengths. Infrared (or heat) radiation conveys information about the composition and structure of Earth-bound solids and gases. It also penetrates the dense clouds of dust that obscure regions where stars and planets are forming. Infrared observation became our best source of information about the chemical composition of remote planets, stars, and nebulae.

Ames started its work in infrared astronomy in 1964, soon after Michael Bader, chief of the Ames physics branch, returned from a very successful airborne expedition to observe a solar eclipse. Ames purchased an old Convair 990 aircraft, named it Galileo and began converting it into a airborne science platform. Along the upper left side of the fuselage, Ames mechanics installed thirteen 12 inch apertures for optical-quality glass in time for the solar eclipse of 30 May 1965. From the beginning, Ames made its airborne science expeditions open to scientists from around the world. They made observations of three solar eclipses, the comet Ikeya-Seki, Mars during

opposition, and the Giacobinidi meteor shower. Using a telescope with a gyrostabilized heliostat for precise pointing, one team of scientists obtained a remarkable set of near-infrared spectra for Venus, showing that the Venusian clouds were not made of water as suspected. Later flights showed, they were made of sulphuric acid droplets. In 1973, the Galileo was tragically lost in a mid-air collision with a Navy P-3 near Moffett Field, California that killed everyone on board. It was replaced by another Convair, named Galileo II, though it was used primarily for Earth observation.

In October 1968 Ames' Learjet Observatory made its first observations. Its apertures were larger than those on the Galileo and opened to the sky without an infrared-blocking quartz cover. Flying above 50,000 feet, teams of two observers aboard the Learjet discovered a host of bright infrared sources. They measured the internal energies of Jupiter and Saturn, made far-infrared observations of the Orion nebula, studied star formation regions, measured water in the Martian atmosphere, and generally pioneered astronomy in the wavelength range of 30 to 300 microns. Ames also used the Learjet to observe events around Earth, like eclipses and occultations.

Encouraged by the success of the Learjet, Ames built the much larger Kuiper Airborne Observatory (KAO). The KAO platform was a military transport aircraft (a Lockheed C-141 Starlifter) housing a 36-inch reflecting telescope in an open port. Soon after its first observations in January 1974, it was renamed in honor of Gerald P. Kuiper, director of the Lunar and Planetary Laboratory at the University of Arizona and a leading light in infrared astronomy. The KAO flew only as high as 45,000 feet, yet was a big advance over the Learjet. It accommodated up to twenty scientists, flew missions over 7.5 hours long, and averaged seventy missions per year. Most importantly, the KAO telescope was balanced on a 16 inch diameter spherical air bearing (the largest ever constructed) and was completely gyrostabilized so it would not be bounced around by air turbulence. Light from the telescope

passed through the air bearing and into the variety of instruments attended by scientists in the pressurized cabin.

Observers on the KAO made many significant discoveries: they found the rings around Uranus; mapped a heat source within Neptune; discovered Pluto's atmosphere; detected water vapor in comets; explored the structure and chemical composition of Supernova 1987a; mapped the luminosity, dust, and gas distributions at the Milky Way's galactic center; and described the structure of star-forming clouds. Jesse Bregman developed a spectrograph used with the KAO telescope that in June 1993 detected water molecules on the surface of Jupiter's moon Io. (Laboratory work in 1988 on planetary ices by Farid Salama first suggested the presence of water on Io.) They also discovered 63 spectral features--atomic, molecular, solid-state--of interstellar materials. Before the KAO, astronomers had identified only five molecular species. KAO observers identified 35 others throughout the galaxy. As important as all these scientific breakthroughs was that a generation of infrared astronomers trained on the KAO.

Ames researchers applied their expertise in airborne observatories to the design of spaceborne observatories. Ames worked with scientists at the Jet Propulsion Laboratory, the Netherlands, and the United Kingdom to design the complete Infrared Astronomy Satellite (IRAS). Ames itself created the IRAS telescope, which has a 60 centimeter mirror and an array of detectors cooled to near absolute zero by superfluid helium. It was launched in January 1983 and, during the one year it survived in orbit, IRAS made the first whole-sky survey ever conducted in the infrared region. In mapping the entire celestial sphere in four infrared bands from 8 to 120 micrometers, IRAS astronomers found 250,000 new infrared sources, suggestions of asteroidal collisions in the zodiacal cloud, particle rings around some stars, and the cool, wispy filaments of the infrared cirrus covering much of the sky. And IRAS returned valuable experience useful in building the next generations of airborne telescopes.

With its infrared astronomy and planetary probes, Ames scientists gathered huge data sets on the molecular dynamics of the universe and on the chemical composition of our solar system. With the airborne science experiments, Ames was calibrating that data with all that we knew about Earth. Ames people wanted to make sure that those hard-won data were well used and, in sorting through every nuance, they made extraordinary advances in planetary science.

Exobiology, Astrochemistry and the Origins of Planetary Systems:

Exobiology continued to be a major focus at Ames, though tied ever more closely to Ames' work in space science. Sherwood Chang led the planetary biology branch and, along with Ted Bunch, did pathbreaking work on organic material and water in meteorites. David Des Marais and Christopher McKay studied the intricate lives of some of Earth's most primitive microorganisms, while Jack Farmer, David Blake, and Linda Jahnke studied the fossil markers for extinct microbial life. This led to a series of bold explorations to find organisms in extreme environments--hot springs, Antarctic deserts, and frozen lakes. Finding organisms in those places was good practice, they thought, for finding life on Mars. Exobiology may have been the science without a subject matter, but Ames indeed found good proxies.

Donald DeVincenzi, the exobiology program manager at NASA headquarters, supported Ames efforts to host workshops and write the papers that continued to define the scientific core of the discipline. A July 1988 meeting with the International Astronomical Union addressed the chemical composition of interstellar dust. Others presented path-breaking work on the presence of carbon in the galaxy. As NASA missions returned new data on solar system bodies--Venus, Mars, asteroids, comets, Europa and the gas planets--Ames exobiologists studied them for clues to the possibilities of life. Similarly, when new missions were planned--like Titan-Cassini or the Mars

rover sample return--Ames exbiologists made sure the biological experiments were well conceived.

Ray Reynolds had done theoretical space science on the formation of planets, at Ames since 1964, well before Ames had begun managing any of its space or observational missions. Hans Mark, like the American public, was fascinated by planetary exploration and supported Reynolds' efforts to build a world-class theoretical studies branch in space science. David Black, who first discovered signs of interstellar material in a meteorite, came to Ames and built a Center for Star Formation Studies. The center was a consortium of Ames and two University of California astronomy departments (at Berkeley and Santa Cruz) and greatly advanced the astrophysical theory of protostellar collapse. They used supercomputers well: they modeled systems ruled by self-gravitation, like galaxies, protostellar clouds, and solar nebula; ran three-dimensional, n-body calculations that followed the motions of billions of stars in their own gravitational fields; calculated the collapse of rotating interstellar clouds to ten orders of magnitude in density; demonstrated that the true shape of elliptical galaxies was prolate rather than oblate; and showed how galaxies collided. Reynolds also hired Jim Pollack.

James B. Pollack, a radiative transfer theorist in the planetary systems branch of the Ames' space sciences division, arrived at Ames in 1970. He always seemed to come up with ingenious ways of connecting some theoretical insight, with the tools Ames had available, and with the scientific challenges people were wrestling with. In the 24 years Pollack worked at Ames before his death, he wrote nearly 300 articles on all facets of planetary science. Postdoctoral fellowships offered by the National Research Council fed much of the scientific vigor at Ames, especially in the planetary sciences. The best young scientists came to Ames for two-year projects, often to work with Pollack, and the best of those hired on. A great many others came to hang experiments on NASA spacecraft or to mine NASA data.

Pollack's drive to understand the origins of planets and the evolution of their atmospheres--especially for the "habitable" planets like Earth, Mars and early Venus--led him to use any variety of numerical, observational, or experimental tool. Pollack worked with Richard Young and Robert Haberle to develop an entire suite of numerical models of the climate and meteorology of Mars. These models comprised a unique resource--used to plan Mars missions, analyze the data they returned, and advance theories on how the climate of Mars changed over eons as the sun warmed up and Mars' atmosphere escaped. The Ames team devised similar numerical models to explain the greenhouse-gas climate of Venus, its high surface heat, its current lack of water, and its acidic atmosphere. Pollack inevitably teamed with other environmentally concerned researchers exploring the atmosphere of Earth. With James Kasting and Thomas Ackerman he initiated some of the first studies of atmospheric aerosols and their effect on the evolution of Earth's climate. Brian Toon contributed his expertise on cloud microphysics, thus bridging efforts in the planetary sciences and Ames' Earth-observation aircraft. These colleagues led the team that later wrote the famous paper on "nuclear winter," suggesting that dust and soot kicked into the atmosphere by a nuclear war would degrade the habitability of Earth as much as the comet impacts that reshaped the climates of other planets and that might have led to the demise of the dinosaurs.

Voyager's grand tour of the outer solar system, coupled with data returned from the Pioneers and observatories, drove a revolution in planetary science focused on the evolution of Jupiter, Saturn, and their moons. Pollack, Reynolds and their collaborators wrote stellar evolution codes to explain the residual internal heat of these gas giants, their growth by accumulation of planetesimals, and the subsequent capture of hydrogen envelopes. Jeff Cuzzi, Jack Lissauer and their collaborators unravelled puzzles in the rings of Saturn and the other gas giants, including spiral waves, embedded moonlets, and their rapid evolution under meteoroid

bombardment. Dale Cruikshank was among the first to identify frozen sulfur dioxide on the surface of Io, the only body in the solar system other than Earth to have intense volcanic activity. Saturn's large moon, Titan, with its smoggy haze and possible ethane oceans, was studied in detail as a fossil of the "primordial soup" which led the Ames group to suggest the Titan probe which led to the design now flying on the Cassini mission.

Ames has also fueled interest in the origin of other planetary systems. Black led the first early studies techniques to find planets around other stars, which presaged future NASA planetary detection missions like Kepler. In addition, the Ames planetary scientists did pioneering early studies of the gravitational and fluid dynamics of protoplanetary disks. Later, they connected the disciplines of astrophysics and meteoritics in studying planetary formation, often by leveraging Ames' in-house expertise in aeronautical fluid dynamics.

Life is made from organic material. Into the early 1990s a unifying theme among Ames researchers was to chart the path of organic material from its origin in the interstellar medium (where infrared astronomy revealed it was formed), through primitive meteorites (available for chemical analysis), and into Earth's biosphere. David Hollenbach and Xander Tielens studied the physical evolution of grains in space. Lou Allamandola picked up the critical question of the chemical evolution of organic materials. It took him many years to piece together laboratory equipment to mimic the space environment and show how organic material could be produced from hydrogen, oxygen, carbon, and nitrogen formed first in the big bang and then subsequently in stars. Allamandola's group showed how polycyclic aromatic hydrocarbons evolved from elementary carbon, and dominate infrared emissions from the Milky Way.

The unique atmosphere at Ames allowed all this work to cross-pollinate--in planetary formation, the evolution of planetary atmospheres, and the chemical, thermal, and gravitational evolution of the solar system.

It also coupled Ames' early pioneering work in exobiology and the chemical origins of life, with the broader discipline later called astrobiology.

]SETI (Search for Extraterrestrial Intelligence)[

In the late 1960s, John Billingham of Ames' biotechnology branch, began to move Ames into the search for extraterrestrial intelligence (SETI). SETI seemed a natural area of interest for Ames. It combined the exobiology quest for life beyond Earth with space science theory for deciding where to look for it, and radio astronomy and computation as the means to search for it. In 1971, Billingham teamed with Bernard Oliver, a former vice president for research at the Hewlett Packard Company and a technical expert in microwave signal processing. They proposed Project Cyclops--\$10 billion for a circular array of 1,000 telescope dishes, 100 meters in diameter, to do a full-sky survey of coherent microwave signals. But neither NASA headquarters nor its scientific advisors would endorse so expensive an effort in such uncertain science.

Billingham also sketched more modest steps that NASA could take to help the many university astronomers engaged in SETI. Collectively, they decided to start searching for nonrandom radio waves in the microwave portion of the spectrum (microwaves travelled well in space and earthlings were already propagating them around the universe). They also decided to search between the natural spectral emission of hydrogen and the hydroxyl radical (OH)--dubbed the water hole--since water is essential for life.

Hans Mark began to appreciate the value of a comprehensive SETI program, not only for what it might discover, but also for what it could teach us about pulses in the universe and as a way to excite children about science. In July 1975, Mark asked NASA headquarters to fund a second international SETI meeting. Fletcher instead obliged Marks to find money from the National Academy of Sciences, but to hold the meeting at Ames. Fletcher did not want NASA to fund SETI prior to a formal commitment authorized by

Congress. Over the next five years, and with Sy Syvertson's encouragement, Ames and JPL (which ran NASA's Deep Space Network) contributed a total of \$1.5 million to design signal processing hardware and algorithms and to hold a series of workshops to map out the most appropriate scientific strategy for SETI. Billingham organized the series of multidisciplinary workshops that brought together a range of scholars--from astronomy, electronics, biology, psychology, and philosophy--to debate the once taboo subject of contacting life beyond our solar system. Two regular attendees were Frank Drake and Philip Morrison, the first astronomers to lend credence to the subject by calculating the probabilities of extraterrestrial intelligence.

NASA began to fund SETI more seriously in 1981--at an average of \$1.9 million per year over the next decade--but its value was constantly challenged. Senator William Proxmire had bestowed a Golden Fleece on the SETI program in 1978, and in 1981 Proxmire successfully passed an amendment deleting SETI's fiscal 1982 funding. Carl Sagan met with Proxmire to argue the merits of the science, and Proxmire agreed to no longer oppose the program. SETI backers became more politically active. They founded the nonprofit SETI Institute near Moffett Field, encouraged university astronomers to turn their ears skyward for highly focused searches, and got Soviet scientists to release data on their efforts. The FAA showed an interest in using frequency analyzers developed for SETI, and the National Security Agency learned about code breaking. SETI was small, well-managed, on budget, and returning interesting science--if not yet evidence of intelligent life, at least far better knowledge about the energy patterns in the universe.

On the 500th anniversary of Columbus' discovery of America, NASA formally launched a SETI program. Renamed the high resolution microwave survey, it was funded out of the NASA headquarters exobiology program, located at Ames and managed by project scientist Jill C. Tarter of the SETI Institute. It received \$12 million in fiscal 1992 against a \$100 million budget over ten years. After two decades of arguing over the mathematical

probabilities of other intelligent life, Ames researchers finally got a chance to actually look for it in a systematic way. While scientists at JPL geared up for a lower-resolution sky survey of the full celestial sphere, Ames developed the equipment and algorithms for a targeted search of solar-type stars. Devices built at Ames would resolve 10 megahertz of spectrum into 10 million channels, simultaneously and in real time. The resulting coverage would have 100,000 times more bandwidth than devices used in previous searches, and was a billion times more comprehensive.

Yet less than a year later, Congress killed NASA's SETI/HRMS program. It died from fervor over the federal deficit and a history of unfounded associations with UFO encounters. The scientific community did not lobby consistently for it--SETI was an exobiology effort that used the tools of radio astronomy. To make it politically palatable, NASA had moved SETI from its life sciences to its space sciences directorate, which gave it low priority. Most damaging, NASA headquarters did not fight very hard to keep SETI in NASA's budget. SETI was small enough to sacrifice easily, and headquarters already felt bloodied from its 1992 budget encounter with Congress. The SETI Institute continues its work with private funding.

]Cosmos/Bion[

A superb example of Ames' ability to do pioneering science quietly and on a small budget was the Cosmos/Bion missions. Every two to four years, between 1975 and 1997, the Soviets shot a Cosmos biosatellite into space carrying an array of Ames life science experiments to study the adaptability of plants and animals to microgravity. A unique spirit of cooperation underlay the success of Cosmos/Bion. Even in the darkest days of the Cold War--following the Soviet invasion of Afghanistan and the Reagan presidency--life scientists from Ames, western and eastern Europe, and the Institute for Biomedical Problems in Moscow continued to collaborate on basic research.

The Soviets had already flown two Cosmos biosatellites before inviting NASA to join the third, to be launched on 25 November 1975. Ames scientists jumped at the chance. The Ames Biosatellite program was cancelled in 1969, the promise of Skylab faded in 1973 as power failures crippled it, and the first biological payload on the Shuttle would not fly until 1983. While Ames had a superb set of ground-based centrifuges for use in studying the biological effects of hypergravity, the only way to study microgravity was in space. In addition, the Soviets offered to pay the entire cost of the spacecraft and launch; NASA need only pay for design and construction of experiment payloads to fly on board. During the 1970s, this never cost NASA more than \$1 million per launch. For this relatively small cost, Ames produced some superb data.

The first launch, Cosmos 782, landed 19.5 days later in central Asia. For security reasons, Soviet scientists recovered the experiments and returned the samples to Moscow. The rat studies exemplified the success of the mission. Eighteen institutions from five countries did studies on every major physiological system in the rat. Many of these experiments were designed by people at Ames: Delbert Philpott of the Ames electron microscope laboratory studied radiation bombardment to the retina; Emily Holton measured bone density and renewal; Joan Vernikos studied gastric ulceration; Adrian Mandel evaluated immunity levels; Henry Leon measured degradation of red blood cells; and Stanley Ellis and Richard Grindeland charted hormonal levels. As experimental controls, the Soviets built a biosatellite mockup that stayed on the ground simulating every flight condition but weightlessness, as well as a small centrifuge for the biosatellite that kept a small control colony at 1 g of artificial gravity. Ames scientists concluded that the stress on the rats came from weightlessness rather than from other flight factors, that spaceflights up to three weeks generally were safe, but that specific results needed to be verified.

After the second flight, Cosmos 936 in August 1977, the results were clearer. Basic physiological systems showed no catastrophic damage, but there was measurable bone loss and muscle atrophy from exposure to microgravity, as well as retinal damage from radiation bombardment. Indeed, the regularity to the Cosmos/Bion flights let Ames biologists constantly improve their protocols and confirm their data. Ames scientists were initially unaccustomed to sending up experiment packages every two years, but they eagerly adapted to the quickened pace of data analysis, publication, experiment proposal, and payload design. New collaborators were added constantly, using new types of organisms--plants, tissue culture, fruit flies, and fish. Every flight used a mass-produced spherical Vostok spacecraft--eight feet in diameter, a volume of 140 cubic feet, with active environmental control, and a payload of 2,000 pounds. Ames project engineer Robert Mah built the cages and bioinstrumentation to fit the space allocated by the Soviets. Kenneth Souza at Ames and Lawrence Chambers at NASA headquarters oversaw the entire program in one capacity or another, and the Soviets no doubt appreciated this continuity of leadership that was so rare within NASA. Eugene A. Ilyin led all efforts in Moscow, and Galina Tverskaya translated with graciousness and precision.

During the 1980s, the cost to NASA rose to an average of \$2 million for each Cosmos/Bion mission, primarily because the mission added two rhesus monkeys as research subjects. The Soviets had never flown monkeys in space; the last time Americans tried, in 1969, the monkey died. So the Cosmos 1514 mission in December 1983 lasted only five days. Not until Cosmos 2044 in September 1989 would the monkeys fly a full two weeks. These flights displayed the remarkable progress Ames had made in bioinstrumentation. Specimens in the earliest Cosmos/Bion flights were flown undisturbed, and descriptive data were collected post-flight. For the later flights, the animal and plant specimens were fully instrumented and data was collected continuously during flight. James Connolly became project

manager in 1985, and more consciously focused the Cosmos payload to complement those flown aboard the Shuttle.

The final Cosmos/Bion mission included a rhesus monkey project devised jointly by American and French scientists. It was originally designed to fly aboard the Shuttle, but was cancelled because of cost and sensitivity concerns. Ames had developed a well-established protocol for the low-cost development of biological experimentation, and quickly modified the rhesus project to fly on Bion 11 for \$15 million, a fraction of the original cost. It launched on 24 December 1996 and landed fourteen days later with the monkeys in good health. However, a day later, during a biopsy procedure requiring anesthesia, one of the monkeys died. A panel of experts convened by NASA headquarters confirmed the validity and safety of the rhesus research. But animal rights activists vilified this death, and Congress questioned why NASA was spending money to help the Russians send monkeys into space. Indeed, with the dissolution of the Soviet Union, the Russians had begun asking NASA to fund a greater portion of the flights. Early in 1997 Congress refused to appropriate \$15 million for the Cosmos/Bion mission planned for the summer of 1998. Few at Ames participated full-time in Cosmos/Bion, so its cancellation had little impact on staffing levels. The cancellation, however, immediately degraded Ames efforts to pursue a systematic research program. The Cosmos/Bion program remained, as it will for the foreseeable future, the single best source of data on the effects of weightlessness on earthly life.

Gravitational Biology and Ecology:

The Cosmos/Bion program was the free-flier portion of a much broader effort at Ames to explore the prospects of earthly life living in space--a program that also included Shuttle-flown and Earth-based experiments. On Earth, Ames continued to explore how humans responded to weightlessness. Dolores "Dee" O'Hara managed Ames' human research facility where, since

the early 1960s, a great many Ames life scientists had refined bed rest into a superb tool for understanding specific responses to weightlessness. Bed rest with a head-down tilt of six degrees, for example, simulates the decreased blood volume incurred during space travel. Joan Vernikos, chief of Ames' life sciences division, used the bed-rest facility to determine which means of plasma expansion made fainting less likely upon return to Earth. She also studied how much gravity was required to remain healthy, supporting NASA's decision to provide intermittent gravity with an on-board centrifuge rather than rotating an entire space station. David Tomko directed the Ames vestibular research facility to coordinate the work of many Ames life scientists studying the body's system of balance and spatial orientation. Likewise, researchers interested in hypergravity worked closely with Robert Welch in the 20 g centrifuge, NASA's only human-rated centrifuge.

Spacelab, flown aboard the shuttle orbiter, carried Ames' experiment payloads in the early 1990s. The Ames space life sciences payloads office provided half of the experiments flown aboard the Spacelab Life Sciences-1 (SLS-1) mission in June 1991. As the first Spacelab mission dedicated to the life sciences, SLS-1 provided an opportunity to study the effects of weightlessness in a comprehensive fashion. The crew hooked on biomedical sensors, many developed at Ames, to study the effects of weightless, and ran experiments on animals and plants in the Ames payload. Bonnie Dalton was project manager and oversaw training of the mission specialist crew, coordination of the experiments, and development of new biosensors. The Ames payload included the research animal holding facility--providing life support to nineteen rats--and the general purpose work station--a glove box to contain liquids during experiments. Because this hardware tested perfectly, Ames could plan on in-flight animal testing in forthcoming missions.

In September 1992, two experiments from Ames investigators flew aboard the STS-47 Spacelab-J mission. Kenneth Souza designed a frog embryo experiment, Greg Schmidt served as payload manager, and Jack Connolly

designed the "frog box." Not only was this the first time live frogs flew in space, but they would also shed eggs that would be fertilized and incubated in microgravity. The experiment showed that reproduction and maturation can occur normally in space--at least with amphibian eggs. Biologists had studied amphibian eggs for more than a century because of the unique way they orient themselves to gravity once fertilized. Patricia Cowings, in an updated version of an experiment flown on Spacelab 3 in 1985, demonstrated that astronauts Mae Jemison and Momuro Mohri who were trained in autogenic feedback--using a "bio-belt" monitoring system built by Ames technicians--could alleviate symptoms of space motion sickness without medications.

SLS-2 (Spacelab Life Sciences-2) flew aboard the shuttle orbiter in October 1993, marking the first time ever that astronauts had collected tissues in space. Before then, all tissues were collected by the principal investigators after the flight landed, making it impossible to separate the physiological effects of microgravity from the hypergravity of lift-off and landing. Furthermore, the shuttle payload specialists first collected tissues on the second day in space--by sacrificing five rats, doing rough dissections, and preserving the tissues--allowing life scientists back at Ames to do the fine dissections and to note how quickly the organisms adapted to space. Tissues were collected again on day fourteen, the day before re-entry, so that life scientists could study how quickly the organisms readapted to the Earth's gravitation. The speeds of adaptation and readaptation were especially notable in experiments on bone density and neurological development. Martin Fettman, a veterinarian, flew as the payload specialist responsible for the rats, and Tad Savage and William Hines of Ames managed the payload of nine experiments.

To better apply to NASA missions all that Ames had learned about the adaptability of various organisms to microgravity, in March 1990 Ames created an advanced life support division. Initially led by William E. Berry and deputy Lynn Harper, the division developed bioregenerative and closed

loop life support systems that would allow astronauts to colonize the Moon or travel for long periods to distant planets. Some systems were simple--like a self-contained salad machine designed by Robert MacElroy and Mark Kliss, to grow fresh vegetables aboard the space station. Some were very complex, like chemical and biological technologies to close the life support loop and enable nearly self-sufficient human habitats in space or on other planets. In addition, Bruce Webbon led efforts to design advanced spacesuit technologies for extravehicular activity and planetary exploration. Likewise, Ames consolidated its work in biotelemetry into a sensors development program, led by John Hines and later renamed the Sensor 2000! program and which developed new technologies for prenatal care in the womb. Throughout its sixty-year history, Ames' instrument builders--in both the life and physical sciences--have been key contributors of spin-off technologies for American industry. Another major contribution was computational fluid dynamics, built on the computing infrastructure at Ames.

]Computing at Ames[

Computational fluid dynamics (CFD)--using computers to depict air flows--was one of NASA's most important contributions to the American aerospace industry. CFD emerged as a scientific discipline largely because of work done at Ames. Two events mark its birth. Harvard Lomax, a theoretical aerodynamicist, in 1969 formed a computational fluid dynamics branch and recruited a world-class group of researchers to staff it. Second, in 1970, Ames negotiated the acquisition of the Illiac IV, the world's first parallel computer. As with most things at Ames, though, these two birthing events merely accelerated an established tradition.

Computers at Ames initially were women, hired to generate smooth curves from the raw data of tunnel and flight tests using electromechanical calculators and mathematics textbooks for reference. In 1947, Harry Goett bought Ames' first electronic computer, a Reeves Electronic Analog

Computer (REAC) and used it to drive simulators to study aircraft stability and control. The first digital computer, an IBM card program calculator, arrived in 1951. Ames' electrical staff lashed together three accounting machines from the IBM product line--a punch card reader, a printer, and an electronic calculator--and taught it to do mechanical reduction of wind tunnel data. To make better use of this machine, in 1952, DeFrance formed an electronic computing machines division, led by William Mersman. By 1955 Mersman's division had succeeded in connecting an Electrodata Datatron 205 computer directly to the 6 by 6 foot tunnel and the Unitary plan tunnels, making it one of the first computers to do real-time compilations of test results. Now, tunnel operators could see almost immediately if their setup generated errors that required rerunning a test.

For seventeen years, Harv Lomax shared a carpool with Marcie Charz Smith, a woman computer who joined Mersman's division and who later became chief of the computer systems and research division. One morning, Lomax complained about having to redo a hand calculation because he used the wrong integral. Once at work, Smith wrote a one-line equation, pulled priority on the IBM calculator, and Lomax had his answer by eight o'clock that morning. Lomax became an instant convert, though other Ames theoreticians remained unconvinced that computers were here to stay. That changed in 1958 when Ames acquired an IBM 704 digital computer capable of running the Fortran programming language, with which they could calculate area rules that reduced drag on wing-body configurations. Calculations were a batch operation, done in octal dumps, meaning they did not know until after the punch cards finished running if there was a programming fault. So Lomax hooked up a cathode ray tube so he could watch the transactions in process and could stop the run if he saw a fault.

Ames opened its first dedicated, central computer facility (CCF) in 1961 adjacent to the circle ringing the headquarters building. At the heart of the CCF was a Honeywell 800 which replaced the Datatron and, until it was

retired in 1977, collected data from all the wind tunnels for on-line data reduction. The CCF also included an IBM 7094, used primarily for theoretical aerodynamics. Ames took its first step toward distributed computing in 1964 by adding an IBM 7040 to front-end the 7094 so that the time-consuming input-output efforts were not done directly on the 7094 computer processor. Ames acquired two smaller, short-lived mainframes--an IBM 360/50 in 1967 and an IBM 1800 in 1968. Mainframe computing took a giant leap forward in 1969, when Ames acquired an IBM duplex 360/67 as surplus from the Air Force Manned Orbiting Laboratory project in Sunnyvale. Now on one time-shared computer, Ames did scientific computing, administrative data processing, and real time wind tunnel data reduction. By adding remote job entry stations around the Center, Ames cut its teeth on distributed interactive computing.

The Illiac IV originally had been built as a research tool in what was then called non-von Neumann computer architecture, and later called parallel processing. Burroughs Corporation built it, with funds from the Defense Advanced Research Projects Agency, based on a design by Daniel Slotnick of the University of Illinois, for installation in the computer science department at the Urbana-Illinois campus. However, student unrest at campuses around the country, especially at the University of Illinois, made DARPA want to put the Illiac somewhere more secure. When Hans Mark heard through his old friend, Edward Teller, that the Illiac was in play, he asked Dean Chapman, new chief of the thermo and gas-dynamics division, and Loren Bright, director of research support, to negotiate an agreement that got the Illiac sited at Ames. Chapman and Bright promised that Ames could not only get the Illiac to work and prove the concept of parallel processing, but in the process would get a return on DARPA's \$31 million investment by generating applications in computational fluid dynamics and in computational chemistry.

The Illiac IV arrived at Ames in April 1972. It was the world's first massively parallel computer, with 64 central processing units, and was the first major application of semiconductor rather than transistor memory. For three years, the Illiac was little used as researchers tried to program the machine knowing the results would likely be erroneous. In June 1975, Ames made a concerted effort to shake-out the hardware--replace faulty printed circuit boards and connectors, repair logic design faults in signal propagation times, and improve power supply filtering to the disk controllers. Not until November 1975 was it declared operational, meaning the hardware worked as specified, but it remained very difficult to use. Designed for research in computer science, it lacked even the most primitive self-checking features. The programming language Burroughs wrote for it, called GLYPNIR, was general enough for computer science research but too bulky for efficient computational fluid dynamics. Most CFDers at Ames found it easier to continue writing Fortran codes and running them on existing serial computers. A few persisted, however. Robert Rogallo began looking at the architecture and the assembly language of the Illiac IV in 1971, even before it arrived. In 1973, he offered a code called CFD that looked like Fortran, and could be debugged on a Fortran computer, but that forced programmers to take full advantage of the parallel hardware by writing vector rather than scalar instructions.

Vector computing meant that programmers wrote algorithms that divided a problem into simultaneous discrete calculations, sent them out to the Illiac's 64 processors, then merged the results back into a single solution. Some problems in CFD were especially amenable to parallel processing. For example, air flow over a wing could be divided into cubic grids--containing air of specific temperatures and pressures--and the algorithms could compute how these temperatures and pressures change as the air moves into a new grid. Ames acquired a CDC 7600 computer in 1975, built by Seymour Cray of the Control Data Corporation and also surplused from the U.S. Air Force. In

translating Illiac-specific CFD language to run on the 7600, Alan Wray wrote VECTORAL, a more general programming language used in some form in all subsequent supercomputers at Ames.

Ames had signalled its commitment to the development of parallel computing, and from then on the supercomputers arrived in a regular flow. Ames installed the Cray 1S in 1981, followed by the CDC Cyber 205 in 1984 (the largest ever constructed), the Cray X-MP/22 in 1984, and the Cray X-MP/48 in 1986. In addition, Ames was the launch customer for a variety of mini-supercomputers introduced in the early 1980s--like the Convex C-1, the Alliant FX/8, the Intel Hypercube, and the Thinking Machines Connection Machine.

All these computing tools attracted computing talent. In June 1983, James Arnold and Kenneth Stevens of Ames' astrophysics division formed the Research Institute for Advanced Computer Science (RIACS), allied it with the Universities Space Research Association, and recruited Peter Denning as its director. RIACS was designed as bridge between Ames, the local universities and the computer industry. RIACS forged a match between the scientific problems of interest to NASA and the potential of new massively parallel computers, then created efficient new algorithms to solve kernel problems in CFD and computational chemistry. Ames researchers focused on theory, while visiting scholars at RIACS pioneered applications.

By the mid-1980s, Ames was one of the world's leading centers in graphical supercomputing, massively parallel processing, and numerical aerodynamic simulation. To give these efforts a physical center, in March 1987 Ames opened the numerical aerospace simulation facility, called the NAS. At the heart of the NAS was one of the world's greatest central processors, the Cray-2 supercomputer. The Cray-2 had an enormous 256 million word internal memory--sixteen times larger than any previous supercomputer--because Ames CFDers had visited Seymour Cray to impress upon him the need for massive memory that was quickly addressable. It was

the first Cray to run the Unix operating system, the emerging open standard in scientific and university computing, which brought new blood into the field of CFD. It had cost \$30 million, computed a quarter of a billion calculations per second, and had to be cooled by liquid nitrogen rushing through clear plastic tubes. Ames had acquired the Cray-2 in September 1985, and had already written the technical specification for the computer that would supersede it. The Cray Y-MP arrived in August 1988, sporting eight central processors, 32 megawords of central memory, and a \$36.5 million price. The Y-MP performed so much better because its bipolar gates allowed faster access to memory than the Cray-2's metal oxide semiconductor memory. The NAS plan was to always have in operation the two fastest supercomputers in the world. By May 1993 the NAS added the Cray Y-MP C90, then the world's faster, and six times faster than the Y-MP.

The NAS building itself was sophisticated. As a home for the Cray, it was kept cool and clean by an air system thirty times more powerful than the systems serving any normal office building of 90,000 square feet. NASA expected to fund ongoing operations at the NAS with an annual appropriation of about \$100 million, so the NAS also housed one of the world's great computer staffs and a range of input and output devices. Support processors had friendly names, like Amelia, Prandtl, and Wilbur--the smaller processors named for aviators, the larger ones for mathematicians. The NAS acquired the earliest laser printers, and pioneered the development of graphical display technologies. F. Ron Bailey, the NAS project manager, directed the NAS to provide supercomputing tools for aerospace research as well as to forge the development of computing itself.

Though the NAS was a physical center for computing at Ames, its tentacles reached into much larger communities. First, around Ames, NAS staff worked directly with the wind tunnel and flight researchers to make CFD an important adjunct to their work. Virtually every other research community at Ames--those working in the life, planetary, astronomical, and

materials sciences--found the staff of Ames' computational chemistry branch ready to find new ways to apply supercomputing to research questions. Plus, the NAS was wired into the larger world of science. ARPA had decided that its Illiac should be accessible via the Arpanet--a network of data cables that linked universities and national laboratories. Hans Mark agreed, based on his experience in using supercomputers in the nuclear laboratories following the discontinuence of above-ground tests. Editors, compilers, and other support software for the Illiac ran only on IBM, DEC, or Burroughs computers. Programmers submitted their code while remotely logged into the IBM 360, usually between the hours of midnight and eight o'clock in the morning, and results were returned back over the Arpanet. This made the scientific community more aware of bandwidth and reliability limitations of the network, and Ames continued to lay cables leading to the Arpanet ring around the Bay Area.

Networking grew stronger as computing pervaded every area of research at Ames. Budget pressures in the mid-1970s forced Ames to do more with less. Jim Hart, on the technical staff of the computation division, encouraged Ames research groups to acquire smaller, interactive (non-batch) computers, with graphics capabilities, and to link them together. Beginning in 1978, Ames acquired several VAX computers from the Digital Equipment Corporation and soon Ames had the largest DECnet in the world--outside of the DEC corporation itself--and a reputation for aggressive development of distributed computing. In November 1982, Ames computer scientists Eugene Miya, Creon Levit and Thomas Lasinski circulated an electronic mail message asking "What is a workstation;" specifically, how a workstation should divide with the network and the mainframe the many tasks of scientific computing. They compiled the comments into the specifications for the first graphic design workstations built by local firms with close ties to Ames--Sun Microsystems and Silicon Graphics, Inc.

By the mid-1980s, however, the dedicated computer-to-computer wiring of the DECnet was being superseded by the packet-switching TCP/IP data transfer protocol that drove the explosion of the Internet. So Ames made a commitment to the technology that allowed closer collaboration with universities and industry: TCP/IP, servers running the UNIX operating system as refined by Silicon Valley firms like Sun Microsystems, and object-oriented client computers like the Apple Macintosh. In 1989, NASA headquarters asked the Ames central computing facility to form a NASA Science Internet project office (NSI) which would merge NASA's DECnet-based network into a secure TCP/IP network. By the time the Cray Y-MP was operational in 1989, more than 900 scientists from 100 locations around the United States were wired into the NAS over the Internet.

Computational Fluid Dynamics:

The technology of computational fluid dynamics (CFD) is transferred via computer codes--generic programs into which aerospace designers enter a proposed design in order to model how air flows around it. The increasing sophistication of these codes--over the two decades Ames committed itself to CFD--reflected not only the application of greater computing power, but also a concomitant flourishing in aerodynamic theory around the Navier-Stokes equations.

The Navier-Stokes equations were introduced in 1846, as a theoretical statement coupling various algebraic equations based on the rules of conservation of mass, momentum and energy. The Navier-Stokes equations are so complex that until the advent of CFD aerodynamic theorists avoided the full set of equations. Aerodynamicists won acclaim, instead, by reducing a flow calculation to its essence and then applying the appropriate partial differential equations--either elliptical, hyperbolic, or parabolic. The only flows they could simulate were for slender aircraft, at small angles of attack, outside the transonic regime, flying in perfect gas with no viscosity and with

no flow separation. Thus, even though the advent of Fortran-based computers in the 1960s made it possible to run these so-called inviscid linearized equations in three dimensions, the simplified configurations on which their calculations were based bore little resemblance to actual aircraft. Nevertheless, Harvard Lomax, continued to refine his calculations of supersonic flows over blunt objects, and Robert MacCormack of the vehicle environment division continued to refine his calculations of viscous flows.

In the early 1970s, CFD took a major leap forward with codes that allowed the velocity, density, and pressure of air flowing over a realistic aircraft design to be calculated, ignoring only viscosity or flow separations. Ames CFDers wrote codes that generated results near Mach 1 and other speeds where tunnel data were unreliable--codes to model wing-body interactions in transonic flow, the blast wave over a hypersonic missile, blunt bodies, and supersonic aircraft configurations. The first experiment run on the Illiac IV was a model of how a sonic boom changes as it approaches ground air. Thomas Pulliam wrote the ARC3D code, which superseded Harvard Lomax's ARC2D code. For the first time, the Illiac allowed three-dimensional portrayals of airflows.

By the late 1970s, with the Illiac IV in more routine operation, CFDers were modeling incompressible flows--flows in which the atmosphere expands or grows denser, adding kinetic energy to the flow and requiring equations that couple velocity and pressure with temperature. This was the first step toward models of supersonic and hypersonic shock waves, as well as models of turbulent boundary layers. By the early 1980s, CFDers had essentially developed a complete set of Navier-Stokes solvers. They had computed time-dependent flows, which depicted how flows changed over time, rather than time-averaged flows, which showed their general tendencies. Furthermore, they had improved their models of turbulence, from simple eddy viscosity models to finite difference models of turbulence in separated flows. Some, like Helen Yee, worked on using nonlinear chaos

theory to study turbulence numerically. Ames and Stanford University, in February 1987, formed a joint venture called the Center for Turbulence Research to specifically develop turbulence models to inject into the Navier-Stokes equations. Once these individual calculations were proved theoretically, Ames CFDers coupled them together to push the Navier-Stokes equations to the limits of their approximation. They also packaged them into routine codes with real industrial significance.

At first, CFDers used tunnel data to validate their computed results. Then, CFDers wrote code that complemented tunnel tests by modeling flows that were impractical to test in a tunnel. Eventually, CFD replaced tunnel tests by generating results that were cheaper and more accurate than data obtained in a tunnel. As airframe companies made more complex aircraft, the number of tunnel and flight tests required in the design of any new aircraft grew at an exponential rate in the 1960s and 1970s. Charles "Bill" Harper who led Ames' full-scale and systems research division, made this argument in a major 1968 address. During F-111 design definition, in the mid-1960s, Ames did 30,000 hours of tunnel tests at a cost of \$30 million. For the Space Shuttle, Ames aerodynamicists planned even more tunnel time. CFD codes, they expected, could eventually eliminate half of this testing in the early design stage.

The first major research program at the NAS validated the design parameters for the National Aerospace Plane, a Reagan administration effort to build an aircraft that could take-off from a runway and reach low-Earth orbit. Using the Cray-2, Ames researchers evaluated airframe designs proposed by the three contractors, calculated thermal protection requirements, and suggested ways of integrating the unique scramjet engine into the shock waves around the airframe. Ames' computational chemistry branch helped by calculating the energies released by air-hydrogen combustion and evaluating the promise of ceramic-ceramic composite

heatshields. Of course, others at Ames then validated all these computational results with tests in the wind tunnels or in the arc jet complex.

Thus, in less than two decades, Ames had brought the field of CFD to maturity. Ames people helped design the supercomputers, visualization equipment, and internetworking that link them. Ames people rebuilt aerodynamic theory around the complete Navier-Stokes equations, wrote the codes for general approximations of airflow, rendered these codes routine design tools, then pioneered codes for more complex problems. Ames CFDers authored code for virtually every flow problem: external as well as internal flows in the subsonic, transonic, and hypersonic regimes. And they coupled these codes to encompass more parts and, eventually, to model entire aircraft and spacecraft. Ames CFDers then worked up theories of numerical optimization, so that designers could specify the performance of a new design and the code would define the best configuration for it. Wing designs, especially, could be optimized computationally so that wind tunnel tests were needed only to verify this performance.

Ames CFDers wrote codes used in the design of virtually every aircraft in the western world. The Cray version of ARC3D was reportedly used to hone the first Airbus, the A300. Ames developed the General Aviation Synthesis Program (GASP) to do quick configuration studies of general purpose aircraft. Industrial users included Beech Aircraft, Avco-Lycoming, and Williams International. The code was used to analyze configurations of subsonic transport aircraft with turbo-props, turbofans, prop-fans, or internal combustion engines. It predicted flight performance, weight, noise, and costs, and allowed easy trade-off studies. Ames CFD work helped Orbital Sciences, a start-up company trying to develop the first new American launch vehicle in two decades. Under NASA's program for small expendable launch vehicles, Ames CFDers adapted code to hone the design of Orbital's air-launched Pegasus rocket and arranged for flight tests with the Pegasus hanging under the Ames-Dryden B-52 aircraft in November 1989. Boeing and McDonnell

Douglas closely followed the state of the art in CFD to refine their commercial transports, but by far the biggest users of CFD were entrepreneurial firms or the airframe firms designing entirely new fighter aircraft.

For designers of supersonic inlets, Leroy L. Presley of Ames devised the first three dimensional internal flow code. For rotorcraft designers, including those at Ames working on VTOL aircraft, Ames CFDers devised various computer codes to model the complex aerodynamics of helicopters.

CAMRAD was a comprehensive code capable of analyzing various rotor configurations--tandem, counterrotating, and tilt rotor--used to predict blade loads, aeroelastic stability, and general performance. ROT22 was a code for rotor field flows, applicable from hover to forward flight, and was three-dimensional, transonic, and quasi-steady.

In 1988, Ames researcher Man Mohan Rai published a code to model the complex pressures, temperatures, and velocities within a jet turbine engine. Engine parts move constantly relative to one another, clearances are very tight, and pressure changes produced by entering air creates unsteady states. Controlled experiments of engine concepts with physical prototypes were very expensive. Rai's model not only solved unsteady three-dimensional Navier-Stokes equations, but did so for complex geometries. It initially required 22 trillion computations, performed on the Cray-XMP at the NAS, before others at Ames set to work simplifying the code to make it a practical tool for industrial design. A highly accurate method for transferring calculated results between multiple grids was the key to Rai's model, and this method later found extensive applications to multiple rotor-stator aircraft.

Some NAS programmers applied their codes to the solution of peculiar problems which then shed light on more general solutions. To depict flows within the space shuttle engines, Ames CFDers Dochan Kwak, Stuart Rogers and Cetin Kiris created a program called INS3D (an incompressible Navier-Stokes solver in general three-dimensional coordinates). Because it was useful in modelling low-speed, friction-dominated flows, in 1993 the group

also applied the code to model air flow over transport aircraft at take-off and to improve a mechanical heart developed at Pennsylvania State University.

Not all of Ames supercomputing focused on modeling airflows. In fact, only twenty percent of the computing time on the Illiac IV was spent on aerodynamic flows. A wide flung group of users, overseen by Melvin Pirtle of the Institute for Advanced Computing, spent the rest of the time on modeling climates, seismic plate slippage, radiation transport for fission reactors, and the thermal evolution of galaxies. When the NAS became available, Ames people wrote codes using maximum-likelihood estimation theory to extract aerodynamic stability derivatives from flight data. Airframe designers worldwide used this code to acquire aircraft parameters from flight data, and thus validate aerodynamic models, update simulators, design control systems, and develop flying qualities criteria. Ames people wrote the hidden-line algorithms underlying most computer-aided design. This code depicted large, complex, engineering renderings faster than ever, and could be applied to aircraft design, architecture, and systems design. It became the best-selling software in NASA history. But by far the biggest nonaerodynamic use of the Ames supercomputers was for computational chemistry.

Computational Chemistry:

Aerothermodynamics and heat shield research brought computational chemistry to Ames. James Arnold had spent several years analyzing the chemical properties of shock-heated air and other planetary gases, and how these atmospheres interacted with ablating materials on heat shields. In 1969 Hans Mark challenged him: "why don't you compute gas properties, rather than relying on measurement?"⁷ Ames had done a superb work building shock tunnels and simulators for atmospheric entry experiments, though at great expense. At spectroscopy meetings, Arnold heard of work at Argonne National Laboratory that showed the potential for reliable computations of the gas properties of small molecules. With his colleague Ellis Whiting,

Arnold saw ways to apply Ames' emergent infrastructure in supercomputing to solve problems in atmospheric entry physics. They were supported by Mark and by Dean Chapman, who had pioneered the theory of aerothermodynamics and later, as director of astrophysics, helped lead Ames into computational solutions. Ames' computational chemistry branch developed, under Arnold's leadership, into a unique resource in NASA.

Academic chemists had computed results that were accurate only for single atoms. Fairly quickly, computational chemists at Ames--including Stephanie Langhoff, Charles Bauschlicher, and Richard Jaffe--developed tools to predict rates of gas-solid chemical reactions involving thirty atoms, predicted forces in molecules and atomic clusters as large as 65 atoms, and simulated material properties involving up to 10,000 interacting atoms. Applying this work to problems of interest to NASA, they designed polymers that were resistant to degradation by atomic oxygen, and improved noncatalytic thermal protection systems. Computational chemists explored several species of ablative materials for the heatshield of the Galileo Probe--which had to be well matched to the atmosphere of Jupiter--and derived the radiative cross sections and absorption coefficients of these species to determine what data was required to design the heatshield.

With these tools in place, David Cooper then led the Ames computational chemistry branch to apply its research to other problems. To develop better aircraft fuels, Ames explored the chemistry of transition metals used in catalysts. To develop better gas properties for aircraft engine flows, Ames computed bond energies and gas transport properties more precisely than ever done experimentally. To develop smaller robotic vehicles, better computer memory devices, and other nanotechnologies, Ames calculated how to make materials bond at the molecular level. To understand the chemical evolution of the solar system, Ames calculated the composition of unidentified spectra observed from space telescopes. Within a decade, Ames

had nurtured computational chemistry into a discipline of major importance to American industry and NASA.

Most important, virtually the entire first generation of CFDers and computational chemists had circulated through Ames in order to use the best machines, to try out forthcoming codes, and to train with the best in the field. And as Ames computational experts saw their fields mature, they reinvented themselves as pioneers in new areas of information technology like artificial intelligence, virtual reality, real-time computing, and distributed networking.

Intelligent Systems and Telepresence:

In the early years of artificial intelligence (AI), symbols rather than numbers were used to represent information, and heuristic rules structured this information rather than the yes/no algorithms used in numerical computation. In 1980 Henry Lum acquired a computer that ran the LISP (for list processing) computing language, and used it to develop the symbolic language of artificial intelligence. Increasingly, Ames researchers focused specifically on communications protocols for integrating various artificial intelligence agents, as needed to guide complex spacecraft or manage complex and changing projects. The goal was to construct rational agents that can acquire and represent abstract and physical knowledge, and reason with it to achieve real-world goals.

Ames formed an information sciences division in June 1987 to spearhead the application of artificial intelligence to space missions. NASA had plans for an autonomous Mars rover, and Ames hoped to provide the technology for many such intelligent agents. The enormity of NASA's just-announced Space Station, for example, required on-board automation for many of the housekeeping functions that would otherwise need to be done by astronauts. Ames' artificial intelligence branch looked at the scheduling of shuttle orbiter ground processing and developed software that, beginning in 1993, saved NASA \$4 million a year in shuttle maintenance. "Shuttle

refurbishing is a difficult problem because you can only predict half of the work in advance," noted Monte Zweben, who led a team of contractors at Ames and the Johnson Spaceflight Center, shared in the largest Space Act award ever granted by NASA, then left to start up a company to program scheduling software for industry.⁸ Peter Friedland led a group working with Johnson to automate Shuttle mission control and reduce human-intensive tasks by forty percent. Silvano Colombano worked with MIT researchers to develop the astronaut science advisor, a laptop computer running artificial intelligence software that helped astronauts optimize spaceborne experiments as they unfolded. Astronauts referred to it as the "P.I. in a Box"--like having the principal investigator on board. While the Ames information sciences division looked for ways to contribute to larger NASA missions, for missions not yet conceived they continued to refine the general principles of artificial intelligence.

Artificial intelligence is a key component in enabling humans and robots to work together as an integrated team of rational agents, when coupled with the technology of virtual reality and telepresence. In 1984, when Michael McGreevy, a researcher in spatial information transfer, learned that a head-mounted display developed for the Air Force would cost NASA a million dollars, he pulled together a team to build its own. The result was VIVED (for virtual visual environment display), the first low-cost head-tracked and head-mounted display, with stereo sound and a very wide field of view. McGreevy soon built the first virtual environment workstation by integrating a number of components, including the VIVED helmet, a magnetic head and hand tracker, a custom-built image conversion system, an Evans & Sutherland vector graphics display system, a DEC PDP-11/40 computer, and software he wrote that generated and displayed three-dimensional, interactive, stereoscopic scenes of commercial air traffic in flight. It was the first major advance in wearable personal simulators since

the laboratory systems built by Ivan Sutherland in the 1960s. By 1987 NASA had boosted the budget for this work thirtyfold.

A whole industry was built around virtual environments, with many of the major innovations inspired or filtered through Ames. Start-up VPL Research of Redwood City commercialized the VIVED design and supplied low-cost virtual reality systems around the world. Scott Fisher, who joined Ames' virtual reality team in 1985, worked with VPL to develop a data glove for computer input. Though the first systems at Ames used Evans & Sutherland vector graphics processors, Ames later used some of the first more powerful and affordable raster graphics systems. Jim Clark credits the many graphics projects at Ames with helping his start-up company, Silicon Graphics, Inc. of Mountain View, California, build image-specific tools and chips. Since the late 1980s, Ames and SGI have worked closely to advance the tools of image generation and virtual reality. Also, Ames work in virtual reality was possible only with new tools for real-time computing. Working with Sterling Software, an Ames support contractor, Ames people developed the mixture of peripherals and interfaces for data acquisition, telemetry, controls, computer animation, and video image processing to compute and portray data points as they were collected.

Virtual reality put Ames at the forefront of human-centered computing. With human-centered computing, people would not consciously interact with the computer itself, but rather interact directly and naturally with real, remote, computer-augmented or computer-generated environments of any kind. NASA saw the value it might have on the space station, by allowing astronauts to control robotic devices around the station. Ames used images generated by CFD to build a virtual wind tunnel--wherein the wearer could walk around a digitized aircraft and see the brightly colored lines depicting airflows. Elizabeth Wenzel of Ames' spatial auditory displays laboratory led a university and industry team developing "virtual acoustics" using headphones to present sounds in three-dimensions. Stephen Ellis and

Mike Sims developed other key components of virtual reality. Ames saw other uses for it--in virtual planetary exploration. As NASA's planetary probes were digitizing the planets--like Magellan's mapping of the surface of Venus--Ames used those data to generate images projected through the personal simulator. It gave anyone--geologists, astronauts, journalists or schoolchildren--the feeling of being there. They used the panoramic views returned from the Viking landers to plan the digitization technology for the Mars Pathfinder, then tested this technology on remotely operated rovers. Prototype rovers imaged the hostile terrain around Death Valley, Antarctica, the volcanoes of Alaska and Hawaii, and underwater in the Monterey Bay. The Marsokhod Rover, lent to Ames in 1993, was a superb platform on which to test this capability--called telepresence.

Work in human-centered computing at Ames took a major leap forward in 1989 with the opening of the human performance research laboratory (HPRL). David Nagel had championed the laboratory to house Ames' aerospace human factors research division. After all, Ames long tradition of work in flight simulators and fly-by-wire technology was a form of telepresence. In addition to supporting Ames' longstanding work in aviation flight training, cockpit resources, and pilot and controller performance, the HPRL brought together researchers working to solve the problems of extended human presence in space, like Vic Vyukal's work in space suit design. There, Ames continued its work on how to make spacecraft more habitable for long-term residents, by investigating microgravity restraints, visual orientations, and changes to circadian rhythms. "We consider it our responsibility to not only promote the productivity of people housed in space," noted Ames environmental psychologist Yvonne Clearwater, "but to assure that once there, they will thrive, not merely survive."⁹

Built adjacent to the human factors laboratory was the automation sciences research facility (ASRF) so that experts in human factors and artificial

intelligence could collaborate. The ASRF opened in January 1992, four months ahead of schedule and \$500,000 under its \$10 million budget. The ASRF provided office space for the growing numbers of artificial intelligence and robotics experts at Ames, led by information sciences division chief Henry Lum. It also provided eleven superb laboratories. In the high bay, Ames built a simulated lunar terrain and used it to test intelligent systems for a rover that would explore planetary surfaces.

1. Continuing Direction: William F. Ballhaus, Jr.

The inculcation of supercomputing into everything Ames did accelerated when Bill Ballhaus, a leader in CFD, became Ames' next director. By 1984, Sy Syvertson had directed Ames for six years, and the Center had flourished under his guidance. But the death of some close friends on the Ames staff, a series of heart problems, and the tragedy and inquiry following the accident in the 80 by 120 foot wind tunnel, all caused him to think it was time for younger leadership. He encouraged headquarters to look at Bill Ballhaus, who had already distinguished himself as a leader.

Ballhaus received his B.S., M.S. and Ph.D. degrees from the University of California at Berkeley in mechanical engineering. His father was a senior vice president for Northrop Aerodynamics and Missiles in Los Angeles, and introduced him to the emergent importance of computing in aerospace. Ballhaus served in the U.S. Army Reserve from 1968 to 1976, earning the rank of captain. He arrived at Ames in 1971 as a civil service engineer with the U.S. Army Air Mobility Research and Development Laboratory. When Ames decided to form an applied computational aerodynamics branch, the Army staff was delighted to let Ballhaus become a NASA employee as branch chief. It proved how close a working relationship had developed between the Army and Ames. After a year, Ballhaus became Ames' director of astronautics in 1980. CFD underwent explosive growth in the 1970s, and

Ballhaus honed his leadership skills through almost constant recruitment. Along with his younger colleagues in the field--Paul Kutler and Ron Bailey--Ballhaus kept abreast of work done in industry and academia, learned to quickly size up whether a researcher wanted time to do basic research or the excitement of engineering application, and teamed them with the best colleagues.

Ballhaus became the director of Ames in January 1984, and helped bring on line several facilities that were key to its research future, like the numerical aerospace simulation facility and the NFAC. Ballhaus initiated Ames' first comprehensive strategic planning exercise, published in March 1988, that suggested that information technology could inject new life into every research area at Ames. And Ballhaus was skilled in reading headquarters, helping Ames people sell their research efforts by describing their ultimate contributions to the International Space Station. Funding for Station-oriented projects was good, and the Ames budget grew quickly in the late 1980s.

Four years into his directorship, in February 1988, Ballhaus was called to Washington to serve one year as acting associate administrator for NASA's Office of Aeronautics and Space Technology. This made him responsible for the institutional management of the Ames, Langley, and Lewis research centers. Once NASA named a permanent associate administrator of OAST, Ballhaus returned as Ames director, but stayed less than six months; on 15 July 1989 he officially resigned. He insisted that the press release about his resignation cite "inadequate compensation for senior federal executives and vague new post-government regulations as factors in his decision."¹⁰ This referred to a 1989 ethics law that barred federal contractors from hiring federal employees who had supervised their competitors' projects. Ballhaus was one of several NASA officials to leave the agency in the week before the new law took effect, prompting the newly appointed NASA Administrator Richard Truly to call a press conference to decry the law as "a crying shame."¹¹

Throughout his tenure as Ames director, Ballhaus amplified a concern expressed by all previous directors--that Ames needed the freedom to hire the best people. Back in October 1961, when vice president Lyndon Johnson asked Smith DeFrance what he could do to help Ames, DeFrance asked for freedom from civil service hiring ceilings. The ceilings remained an issue, and Ames was never so constrained by funds or resources as it was by civil servants to manage them. By the 1980s, Ames still suffered under the ceilings, but now lacked the freedom to pay potential hires competitive wages. Ballhaus fought to secure special salary rates applicable to half of the Ames workforce, limited approval to match industry salary offers, hiring authority for most of the occupations at Ames, and approval to test out a more flexible compensation and promotion plan. He led his staff in improving the quality of life around Ames--opening a child care center, working more closely with the National Federation of Federal Employees, getting everyone involved in a regular strategic planning process, and encouraging diversity so that Ames was awarded the NASA trophy for equal employment opportunity in both 1984 and 1989. Statutes limited what he could do with executive pay, however, and when Congress defeated the Reagan administration proposal for a pay raise many in Ames' senior executive service left prematurely. "I would have preferred a more graceful exit," Ballhaus wrote to announce his departure. "The Center's success in the future will depend upon our ability to continue to recruit and retain the high-quality people that Ames is noted for. In leaving, it is the close association with the outstanding people who make up this Center that I will miss most."¹² From there Ballhaus joined the Martin Marietta Astronautics Group in Denver as vice president of research and development, then rose steadily up the ranks of Lockheed Martin Corporation.

Dale L. Compton:

Dale Compton, who had served as acting director when Ballhaus moved to Washington, replaced him as Ames director. Compton, too, was a product of Ames. He came to the Center fresh out of Stanford University with a master's degree in 1958, one of the first students taught by former Ames aerodynamicist Walter Vincenti. He then returned to receive his Ph.D in 1969. Compton worked as an aeronautical engineer and had a penchant for participating on project teams--as an aerothermodynamicist for ballistic missiles and NASA's Mercury, Gemini and Apollo human space programs, and as manager on the infrared astronomical satellite program (IRAS). He entered management ranks in 1972 as deputy director of astronautics, became chief of the space sciences division, became director of engineering and computer systems, was named Ballhaus' deputy in 1985, and was officially named director on 20 December 1989 at ceremonies marking Ames' fiftieth anniversary.

Victor L. Peterson joined Compton as deputy director in 1990. Peterson, too, was a product of Ames. He joined Ames in 1956 upon graduating from Oregon State University, and distinguished himself through research in aerodynamics, high-temperature gas physics, and flight mechanics. He was internationally known as an advocate of large scale scientific computing in all scientific disciplines, but especially in computational fluid dynamics.

Compton, like Ballhaus before him and Syvertson before him, understood how Ames nourished innovation and personal reinvention. Each had grown his own career at Ames, and each knew how to let those under his direction blossom. And NASA headquarters provided new opportunities and resources for myriad Ames researchers to flourish as the Bush administration looked to space adventures--following the end of the Cold War in 1989--to once again display America's technological prowess.

In April 1989, early in his term as president, George Bush appointed Admiral Richard H. Truly--a former Shuttle astronaut and the person most

responsible for restoring the Shuttle to viability after the Challenger accident--as the new NASA administrator. Then, on 20 July 1989, the 20th anniversary of the Apollo 11 lunar landing, Bush made a Kennedy-esque announcement about America's commitment to return to the Moon "this time to stay, " for a human mission to Mars, and for the expanded internationalization of the Space Station Freedom. These long-term, complex space projects made good use of the basic research done at Ames in microgravity, robotics, and planetary science, and Ames' budget grew apace modestly into the early 1990s.

Yet Compton was seen by some around Ames as too conservative in his vision--a "tunnel hugger"--one who thought Ames' position within NASA depended on the immovability of the superb wind tunnel infrastructure around Ames. Compton had seen the more project-oriented NASA Centers go through booms and busts as Congress approved and disapproved major projects and thought Ames--fundamentally a basic research organization--would be especially disrupted by such cycles. He had doubts about what sort of institutional follow-on would come from any of the projects emanating from Ames' space scientists, and he understood that if the Jet Propulsion Laboratory needed work that NASA headquarters would send space projects there to be managed. He had fought hard for SIRTf (the space infrared telescope facility), the Mars Observer, and the Magellan Venus all to be managed at Ames, but all were lost to JPL. As deputy director, Compton had nurtured the airborne telescope SOFIA only to see, as director, it cut at the last minute before submission of the final NASA budget. Moreover, the various wind tunnel and simulator restoration projects added \$300 million to Ames' budget in the late 1980s, so Compton made sure these efforts were managed well.

Beginning in the late 1980s and continuing through the mid 1990s, NASA headquarters put Ames through a series of roles and mission exercises. The goal, ultimately, was to make all NASA Center directors more agile in being able to modify their Centers' expertise to accommodate

changing national needs. While the strategic plans emerging from these exercises always reiterated Ames' interest in aeronautical research, the plans always seemed a bit empty. A great many people at Ames, especially those in life sciences and information technology, began to wonder how they fitted into that picture of Ames. Into the 1990s, Ames began to directly address the relationship between its future and its past.

Endnotes

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